Canada

ADVANCED CERAMICS

REPORT No. 3/86

OFFICE OF INDUSTRIAL
INNOVATION

INNOVATION

Government of Canada
Regional Industrial Expansion

Gouvernement du Canada
Expansion industrielle régionale

86-05262/

Advanced Ceramics

Office of Industrial Innovation
Department of Regional
Industrial Expansion
January 1986

This report was written by Dr. M.K. Murthy of M.K.M. Consultants International under contract to the Department of Regional Industrial Expansion for its Technology Assessment Directorate. The directorate recognizes the quality of Dr. Murthy's work; however, the opinions he expresses in this document are not necessarily those endorsed by the department.

FOREWORD

Many industry leaders view advanced industrial materials, with microelectronics and biotechnology, as the technological core of the next industrial revolution.

Both economic and strategic considerations are spurring rapid development and diffusion of advanced materials and their applications abroad. In the medium and long term, this surge will have a significant effect on Canada's traditional resource sectors. As well, sectors of the Canadian manufacturing industry might well be rejuvenated by using new materials, and new markets could be created for the Canadian raw materials required to produce them.

This report is the third of a series on emerging technologies published by the Technology Assessment Directorate of the Office of Industrial Innovation. It analyses, from an international perspective, the opportunities and threats facing Canadian industry in advanced ceramics. This field is becoming an increasingly important member of the family of advanced industrial materials technologies.

The Technology Assessment Directorate, as part of its effort to promote and publicize technological advancements, emphasizes the development of networks of interested individuals, the bringing together of potential technology users with developers, and the encouragement of an environment conducive to technological developments.

The principal aim of this report is to make people and businesses more aware of commercial opportunities in advanced ceramics. A secondary goal is to introduce readers to the existing network of people working in the field. Readers who wish to join the network, should feel free to contact the Office of Industrial Innovation.

Office of Industrial Innovation
Department of Regional Industrial
Expansion
Ottawa, Ontario, K1A 0H5
Telephone: (613) 995-3741

ACKNOWLEDGEMENT

The author wishes to acknowledge the assistance of the following organizations in the preparation of this report:

- the Office of Industrial Innovation and the Resource Processing Industries Branch of the Department of Regional Industrial Expansion;
- the Canada Centre for Mineral and Energy Technology of the Department of Energy, Mines and Resources;
- the Division of Mechanical Engineering, the Industrial Materials Research Institute and the National Aeronautical Establishment of the National Research Council of Canada;
- the Department of External Affairs and the Canadian Embassies in Tokyo, Paris, Bonn and Stockholm;
- the Ontario Research Foundation;
- le Centre de recherche industrielle du Québec;
- Queen's University;
- McMaster University;
- University of Toronto;
- University of British Columbia;
- the U.S. National Materials Advisory Board;
- the U.S. National Bureau of Standards;
- the Centre for Ceramics Research of Rutgers University;
- the Japanese Ministry of International Trade and Industry.

TABLE OF CONTENTS

PAGE NO.

EXECUTIVE SUMMARY i

1. INTRODUCTION 1

2. METHODOLOGY 2

3. DESCRIPTION OF ADVANCED CERAMICS 3

3.1 Definition 3

3.2 Classification 6

3.3 Materials and Technology 13
3.3.1 General 13
3.3.2 Ceramic Processing. 13
3.3.3 Advanced Structural Ceramics. 17
3.3.4 Advanced Functional Ceramics 33

4. INDUSTRIAL APPLICATIONS 38

4.1 General 38

4.2 Automobile and Other Applications 38
4.2.1 Advantages of Using Ceramics 38
4.2.2 Current Status of Development of Engines . . . 41
4.2.3 Outlook 51

4.3 Cutting Tools and Machinery Parts 56
4.3.1 Background 56
4.3.2 Ceramic Cutting Tools 56
4.3.3 Advantages of Advanced Ceramic Cutting Tools . 57
4.3.4 Industrial Activity 57

4.4 Electronic Applications 60
4.4.1 Background 60
4.4.2 Current Status and Outlook 63

4.5 Industrial Products 64

4.6 Energy and Space Products 65

4.7 Consumer Products 65

5. MARKET POTENTIAL AND OUTLOOK 67

5.1 General 67

5.2 Market Data for the United States 67

5.3 Market Data for Japan 71

6. INTERNATIONAL PERSPECTIVE 81

6.1 General 81

6.2 Advanced Ceramics in the United States 84
6.2.1 General 84
6.2.2 Government Programs, Policies and Initiatives. 85
6.2.3 Industrial Activity in Advanced Ceramics . . . 88
6.2.4 Professional and Technical Societies 91
6.2.5 University Activities in Advanced Ceramics . . 91

6.3 Advanced Ceramics in Europe 92
6.3.1 General 92
6.3.2 Advanced Ceramics in West Germany 92
6.3.3 Advanced Ceramics in Sweden 95
6.3.4 Advanced Ceramics in the United Kingdom . . . 99
6.3.5 Advanced Ceramics in France 101

6.4. Advanced Ceramics in Japan 104
6.4.1 General 104
6.4.2 Government's Role and Influence 105
6.4.3 Government Coordination and Management of Advanced Ceramics Programs - Role of MITI . 106
6.4.4 Review of MITI Programs on Advanced Ceramics 111
6.4.5 Industrial Activity in Advanced Ceramics . . 114
6.4.6 University Participation in the Development of Advanced Ceramics 120

7. CANADIAN PERSPECTIVE 124

7.1 General 124

7.2 Profile of the Canadian Ceramic Industry 124
7.2.1 Profile of Traditional Ceramic Industry . . . 124

7.3 Profile of the Canadian Advanced Ceramic Industry . 125
7.3.1 General 125
7.3.2 Manufacturers of Ceramic Powders for Advanced Ceramics 126

7.3.3 Manufacturers of Electronic Ceramics and Components 128
7.3.4 Manufacturers of Advanced Structural and Industrial Ceramics 132
7.3.5 Manufacturers of Cutting Tools 135

7.4 Advanced Ceramics R & D in Federal Government Laboratories 138

7.5 Advanced Ceramics R & D Activities in Canadian Universities 142

7.6 Advanced Ceramics R & D Activities in Provincial Research Organizations 145

7.7 Threats and Opportunities for Canadian Industry . . 147
7.7.1 General 147
7.7.2 Impact of International Development 150
7.7.3 Opportunities in Advanced Functional Ceramics 154
7.7.4 Opportunities in Advanced Structural Ceramics 157

7.8 Opportunities, Barriers and Options 161

BIBLIOGRAPHY 165

APPENDIX A 168

APPENDIX B 174

LIST OF TABLES

PAGE NO.

Title

1. Properties of Advanced Structural Ceramics 18
2. Properties of Ceramic Substrate Materials 34
3. Ceramic Technology Payoff of Some Typical Engines 40
4. Scope of Programs of West German Ceramic Manufacturers in the National Program 46
5. Research Trends of Japanese Companies in the Development of Ceramic Engine Parts 49
6. Ceramic Components Used in Automobiles 50
7. Major Suppliers of Advanced Ceramic Cutting Tools to the US Market 59
8. Applications of Electronic Ceramics 62
9. Industrial Products Made from Advanced Ceramics 66
10. Comparison of High-Technology Ceramics Markets, 1980 68
11. Projection of World Market for Advanced Ceramics 68
12. Summary of Market Potential for Selected Ceramic Parts for US . 70
13. A Range of Market Penetration for Ceramic Components by the Year 2000 for US 70
14. US Shipments of Advanced Ceramics by End Use to the Year 2000 (1980 dollars) 73
15. Market Size of Fine Ceramics in Japan for 1980 and 1982 74
16. Projected Market Data for Fine Ceramics for 1983 75
17. Forecasts of the Size of the Fine Ceramics Market in Japan . . 78
18. Present International R & D Efforts in Advanced Ceramics by Application Area (1984) 83
19. Major US Firms Engaged in Advanced Ceramic Engineering Products Research and Production 90
20. List of Industrial Participants in the West German National Program 93
21. Budget in the West German National Program on Advanced Ceramics for Engines 93
22. List of Universities and Government Laboratories Working on Advanced Ceramics in the United Kingdom 102
23. List of Industrial Companies Working on Advanced Ceramics in the United Kingdom 102
24. Japanese Government Involvement in Ceramics 107
25. Members of the Engineering Research Association for High-Performance Ceramics 110
26. Classification of Company Types in the Japan Fine Ceramics Association 112
27. Performance Objectives of MITI High-Technology Ceramics Program 115
28. Relative Size of the Ceramics Industry in Japan 117
29. Number of Researchers by Line of Business in Japan 118
30. Japanese Companies Active in Commercialization of Advanced Ceramics 119
31. Motives for Entering the Fine Ceramics Industry 121
32. Number of Higher Education Students and Holders of Academic Degrees in Japan, USA, UK, France and West Germany 122
33. Major Japanese Universities with Ongoing Research Programs in Ceramics 123

LIST OF TABLES (cont 'd.)

Title | PAGE NO.

34. Manufacturers of Ceramic Powders for Advanced Ceramics 127
35. Companies Manufacturing Electronic Ceramics and Components . . 130
36. Companies Manufacturing Advanced Structural and Industrial Ceramics 134
37. Canadian Manufacturers of Cutting Tools 136
38. Advanced Ceramics R & D Activities in Federal Government Laboratories 139
39. Advanced Ceramics R & D Activities in Canadian Universities . 143
40. Advanced Ceramics R & D Activities in Provincial Research Organizations 146
41. Opportunities in Advanced Functional Ceramics for Canadian Industry 156

LIST OF FIGURES

PAGE NO.

Title

1. Scope of Traditional Ceramics 4
2. Functional Scope of Advanced Ceramics 5
3. Functional Applications of Advanced Ceramics 7
4. Scope of Advanced Ceramics for Mechanical and Structural Applications 8
5. Scope of Advanced Ceramics for Electrical and Electronic Applications 9
6. Scope of Advanced Ceramics for Thermal Applications 10
7. Scope of Advanced Ceramics for Chemical Applications 11
8. Scope of Advanced Ceramics for Magnetic, Optical and Biological Applications 12
9. Ceramic Fabrication Processes 14
10. ASEA Ceram Hot-Isostatic Pressing Process 15
11. Specific Surface and Oxygen Content of Commercial Silicon Nitride Powders 20
12. Scope of Scientific and Technological Studies for the Commercialization of Advanced Ceramics 24
13. Industrial Applications of Advanced Ceramics 39
14. Benefits Resulting from Using Advanced Ceramics in Engines . . 42
15. Trends in Material Capability for Gas Turbine Engines 43
16. Energy Efficiency Improvement in Diesel Engines with Advanced Ceramics 48
17. Cutting Tool Speed as a Function of the Year of Introduction of Material into Practice 58
18. Production Cost Using Various Cutting Tool Materials 58
19. Types of Electronic Ceramics 61
20. Market Penetration for Ceramic Applications under Alternative Cases (USA) 72
21. MITI Market Projection Data for Advanced Ceramics in Japan . . 77
22. Timeframe for the Introduction of Advanced Structural Ceramic Components 80
23. Relative International Level of Effort in the Development of Advanced Structural Ceramics 82
24. US Government Funding of Advanced Structural Ceramics Research and Development 87
25. Advanced Structural Ceramics Development Program in Sweden . . 98
26. Advanced Ceramics Programs in Japan Sponsored by MITI 113
27. Schedule of MITI Development Program 115
28. International Pressure on Canada for World Market Share 152

EXECUTIVE SUMMARY

BACKGROUND

The term 'ceramics' applies to a variety of inorganic substances. The current generally accepted definition is: "an inorganic, non-metallic material processed or consolidated at high temperatures." There are two groups of ceramics, traditional and advanced.

Traditional ceramics include such things as pottery, dinnerware, sanitary ware, bricks, insulation, refractories and glass - articles that have been used for generations.

Advanced ceramics are a diverse group of inorganic materials comprising or combining oxides, carbides, nitrides and graphite. The revolution in advanced ceramics began more than a decade ago to fill important industrial needs: to produce materials with superior mechanical, thermal, electrical, chemical and optical properties. These materials would help lead the technological advance by making products and processes more competitive, more reliable and less expensive. Industrial achievements so far, particularly in the development and commercialization of electronic ceramic materials and components, have been remarkable. The market share of electronic ceramics in 1980 was about 70 per cent of the world advanced ceramics sales of US$ 4.25 billion*. Japan, far and away the leader, captured almost 70 per cent of this market.

The huge global market for advanced ceramics has caused the current international surge of interest, estimated to be $30 billion by the year 2010. Scientific and technological developments to date have demonstrated not only the technical feasibility, but also the potential economic, social and environmental benefits of advanced ceramics for certain applications. Examples include automobile engine components, cutting tools, wear- and corrosion-resistant parts for machinery and industrial equipment, opto-electronics for communication, and sensors for detection and control applications.

There is intense world-wide competition to develop and commercialize advanced ceramic components. The United States, Japan, West Germany and Sweden have already established national strategies and committed significant resources and investments. The United Kingdom, France and Italy are also becoming active; the UK is expected to make a national commitment shortly. Canada is at a disadvantage, because it is one of the few Western industrialized nations without a national strategy.

The countries that have become involved in advanced ceramics have done so largely because of economic concerns. Industries want to protect the technological edge in their domestic markets, save energy costs and reduce dependence on imported strategic materials. The potential of advanced ceramics to spur the growth of present and future high-tech industries is another strong motivating force.

---

* Unless specified otherwise, all dollar figures are in US funds.

For some functions, advanced ceramics can outperform competing metals and polymers, and so are expected to cut into their market. They have many uses within several industrial sectors: transportation, manufacturing, electronics, communications, and energy. Because of this diversity, even modest market penetrations are expected to significantly affect most industries. Hence, greater international acceptance of advanced ceramics is expected to seriously harm traditional Canadian industrial material suppliers. Some businesses will prosper, though. Certain sectors of Canadian industry might be rejuvenated by using advanced ceramics. Perhaps more important, new markets can be created for Canadian raw materials required in the manufacture of advanced ceramic components.

INDUSTRIAL APPLICATIONS

Advanced ceramics are generally used as components. Applications can be grouped into six categories:

- Electronics;
- Automobile and Other Engines;
- Cutting Tools and Machinery Parts;
- Industrial Products;
- Consumer Products;
- Energy and Space.

Electronics

There has been significant commercial production of electronic components since the late 1950s. The markets for these products are expanding rapidly, and growth in the coming decades is projected to be excellent, exceeding 15 per cent per year. The biggest current use of advanced ceramics is for integrated circuit packages, capacitors and resistors. New applications include sensors and integrated optics. The demand for sensors is increasing for applications in robotics, automobiles, environmental detection and control, automation, medical implants, and other industrial and consumer markets. Integrated optics, which are optical guided-wave devices that perform processing functions on the light beams that they guide, are expected to play a revolutionary role in fibre optics communication systems.

Automobile and Other Engines

Advanced ceramic components based on silicon nitride (Si_3N_4), silicon carbide (SiC) and zirconia (ZrO_2) have been under development since the early 1970s for gas turbine, diesel and gasoline engines. The technical and economic factors behind the current feverish efforts are the need for improved energy efficiency, multifuel capability, lower component costs and reduced dependency on imported raw materials.

To date more than $500 million has been spent, world-wide, towards the development of materials and engineering technologies to demonstrate technical feasibility. Successful engine-in-vehicle demonstration projects in the United States, Japan, West Germany and Sweden are spurring early commercialization. Japan has already introduced several components commercially into diesel engines, and turbochargers are in prototype production. The consensus for future developments is roughly as follows:

Period	Development
1984 - 1987	Ceramic Parts
1987 - 1990	Ceramic Components
1990 - 1995	Systems
1995 - 2000	Small Gas Turbine Engines

Despite their successes, technical experts are aware of serious unsolved problems: reproducibility in manufacture, reliability in service and cost. They are optimistic, however, that satisfactory solutions will be found within the periods listed above.

Cutting Tools and Machinery Parts

This is another area where advanced ceramics are being used more and more because of their hardness, toughness, and high temperature strength. Cutting tools made from material based on silicon nitride are now commercially used because they work at higher speeds, reducing machining costs and increasing productivity. Production costs can be reduced by 60 to 75 per cent. More important, the increase in automated numerically controlled machine tools, where reliability and performance greatly influence production costs and productivity, makes the use of advanced ceramic cutting tools almost a necessity. Wear or corrosion of present-day metallic parts is estimated to cost more than $10 billion annually in the US alone. For this reason, advanced ceramic components, such as seals and bearings, and liners for pumps in corrosion/erosion applications are finding increased use.

Industrial Products

There are new applications for advanced ceramics based on silicon nitride, silicon carbide and zirconia because of their resistance to erosion and corrosion. In the iron and steel, aluminum and other non-ferrous metal processing industries, they are being used as nozzles, conveyor rollers, slide gates, etc. In the chemical processing and related industries they are used in heat exchange and regenerator applications. In the oil and gas industry, they are used as components in highly erosive environments. Other important applications include: pulverized coal burners; nozzles for welding; sand blasting and spray drying; high-temperature fans for furnaces; metal extrusion and wire drawing; special heaters; and precision jigs in the manufacturing of electronic components.

Consumer Products

There is a fast-growing business in consumer applications especially in Japan. Some of the products already produced commercially are scissors, knives, parts for golf clubs, fishing rods, components for electric shavers and blades for skates.

Energy and Space

Advanced ceramics are used for batteries, fuel cells and solar collectors in energy industries; and for heat shields, rain erosion prevention, radomes, IR windows, and other applications in aerospace and space industries.

MARKET POTENTIAL

Market data from the Japanese Ministry of International Trade and Industry (MITI) and the US Commerce Department are summarized below. No reliable statistics are available for the rest of the world.

Country	1990	2000
	(1980 billions	of dollars)
Japan	5.2 - 7.2	11.2 - 16.8
USA	2.5 - 3.2	5.0 - 7.5
TOTAL	7.7 - 10.4	16.2 - 24.3

The data for Japan are based on total sales — domestic and export. The US data are for domestic consumption only. The range for both sets of statistics accommodates two important uncertainties. First, some of the technologies are not fully developed and quick solutions to several technical barriers are not yet in sight. Second, in most cases, advanced ceramics will be competing against well-established metals technology so market penetration will depend upon the trade-off between performance and cost.

Most of the growth in advanced ceramics in the coming decades is expected to be in electronic and other functional ceramics (e.g., sensors, integrated optics, bioceramics). In Japan, MITI projects that only 25 per cent of the market will be for advanced structural ceramics related to engine parts and components, wear parts, cutting tools, etc. Below is a projected breakdown of the Japanese market:

Year	Electronic Ceramics	Structural Ceramics
	(1980 billions	of dollars)
1988	3.0	1.0
1990	3.9 - 5.4	1.3 - 1.8
2000	8.4 - 12.6	2.8 - 4.2

A roughly similar trend has been forecast for the US market. Of an estimated total market of $7.5 billion in the year 2000, 47 per cent ($3.5 billion) will be in electronic ceramics.

There is consensus that the long term (10-20 years) market for engine applications is good and alone could amount to as much as $7 billion by the year 2000 in just the US and Japan. In the short term (0-5 years), manufacturers of advanced ceramics parts and components will likely have to underwrite considerable investments because the volumes will be small and production costs high. The economic picture should brighten in the medium term (5-10 years) because of expected improvements in technology that will increase manufacturing efficiency.

To recover some of their large investments, the advanced ceramics manufacturers are commercializing the existing materials and technology for non-engine applications. They include industrial products (e.g., regenerators, heat exchangers and wear- and corrosion-resistant parts), consumer goods (e.g., knives, scissors, sports equipment and household products) and specialty items (e.g., artificial body parts, such as teeth roots, hip joints and bones).

There is no question that advanced ceramics are going to play a significant role in national economies in the coming years. Businesses other than ceramics manufacturers have begun to invest in these advanced materials. For instance, the textile, petrochemical and metal industries want to apply existing technology to achieve higher added value, create more profitable products and upgrade their product lines. For other industries, the move into advanced ceramics is rapidly becoming not an option, but a necessity. To compete, processing and assembling industries are being forced to develop new materials on their own. This trend is well established in Japan and is developing in the US and Europe.

INTERNATIONAL PERSPECTIVE

There is a compelling financial reason for the intense international competition to develop advanced ceramic technology and to introduce it into the market place: a potential global market of $30 billion by the year 2010, plus about $60 billion in productivity benefits and energy savings. Joint industry-government initiatives have put the United States, Japan, West Germany and Sweden at the forefront of research, development and marketing. Great Britain, and to a lesser extent, France and Italy have recently joined the race. Probably more than 2 000 scientists and engineers are working in Japan in advanced ceramics, supported by about an equal number of technicians. In the US, up to 1 000 scientists and engineers are principally engaged in R & D on advanced ceramics; 1 000 to 2 000 others are peripherally involved. In Europe, there are no more than 500 specialists working in advanced ceramics; in Canada, between 50 and 100.

United States

The United States has been a world leader in advanced ceramics research and development and commercialization since the 1950s. R & D of advanced ceramics for engine applications began in the 1970s with full government support; since then several demonstration projects have been successfully completed. The government alone has spent more than $300 million. At present there is serious concern, both in industry and government, that despite scientific and technological leadership commercialization is lagging.

Several government organizations, including NASA and the departments of defence and energy, fund R & D on advanced ceramics both in private and in-house laboratories. Total government support for R & D is estimated to be close to $100 million per year. US industry, including 100 major companies, is estimated to spend another $100 million annually. Reasons for increased funding include:

- Possible harm to industry because of competition from Japan, West Germany and Sweden;
- Defence needs and national security considerations, including strategic materials dependency;
- Potential savings through energy efficiency.

Three government studies have recently identified the need for a change of official policy. They call for more direct support for the advanced ceramics industrial sector to counter international competition, particularly from Japan. The government is promoting the establishment of ceramic centres at universities, and a national centre has been set up at Oak Ridge National Laboratory.

Japan

The development and commercialization of high value-added technologies, such as advanced ceramics, form the centrepiece of Japan's industrial strategy. Both industry and government are co-operating to make this strategy work. The interest and commitment of industry is driven by the market forces, particularly the need for these materials to support other high-technology industries and the huge potential market for engines. The government is involved because it believes that advanced ceramics will help solve many of Japan's energy problems and support the development of frontier industries (e.g., the search for petroleum substitutes, aerospace and space, biotechnology and electronics). The government also recognizes that advanced ceramics, by themselves, have the potential to generate whole new industries.

Japan, the world leader in advanced ceramics, has mounted a concerted national campaign to maintain its dominant position. Current estimates put Japan's share of the world market at 50 per cent. It has already started to manufacture some ceramic components for diesel engines (300 000 glow plugs and 20 000 precombustion chambers per month). The

Japanese industries and banks have made a commitment to ensure success by purchasing and pricing strategies, and by creating vigorous educational programs to provide technical talent. The Japanese are apparently willing to wait longer for an emerging technology industry to develop and become profitable than are companies in the US and Europe. Japan is already investing the most - in both money and manpower - on advanced ceramics R & D: the government spends about $50 million annually; industry is estimated to spend between $100 and $250 million.

The Ministry of International Trade and Industry (MITI), is leading the government involvement through its Fine Ceramics Office. Several laboratories under MITI support industry in R & D, and the ministry has taken other initiatives to promote advanced ceramics in Japan.

Industrial interest in advanced ceramics is reflected by the membership of the Japan Fine Ceramics Association. The 172-member group comprises 41 companies in ceramics manufacturing, 41 in chemicals, 25 in electrical appliances, 23 in steel and non-ferrous metals, 23 in machinery, 7 in automobiles, 7 in heavy industry and 14 in other sectors.

West Germany

A national R & D program from 1974-1983 was designed to develop and commercialize advanced ceramic components for automotive engines and other high performance applications. This joint venture between government, industry, universities and research institutes had a total budget of $33 million. Government and industry shared the costs equally. Three engine manufacturers (Volkswagen, Daimler Benz and MTU) and seven ceramic manufacturers participated.

A new 10-year industry-government co-operative program to develop advanced materials (ceramics, powder metallurgy, composites and high temperature materials) was recently launched. The budget is $23 million per year. Another $4.7 million has been allocated for projects related to corrosion and wear. The specific budget for advanced ceramics is not available yet.

Sweden

Next to Germany, Sweden is the most active country in Europe in the development of advanced ceramics for engine applications, primarily because of its important automotive industry. The Swedish national program, which began in 1976, is a co-operative effort between industry, government and universities. About 14 companies are participating, including Volvo, SAAB-SCANIA and ASEA. Some of the developments are close to commercialization.

United Kingdom

The development of advanced ceramics for engine applications began in the United Kingdom in the early 1960s. Though technologically successful, it was discontinued because of poor market prospects. Both industry and government have now recognized the need for a new national commitment to advanced ceramics: The UK cannot afford to lag behind its competitors. A surge in the R & D investment will give industry an opportunity to leap-frog foreign competition and so recover its share of the world market and trade. Two industrial clubs have been formed. The 'Rolls Royce Club' is a consortium of 10 companies that will develop gas turbine engines with a government grant of about $11 million in the 1985-1988 period. The other club, known as the Consortium for Ceramic Applications in Reciprocating Engines, consists of about 20 companies including car, auto parts and ceramics manufacturers. The government has approved the program, but the budget is not yet known.

France

France does not have a national program devoted to advanced ceramics. However, several industries are involved in their development. Financial support comes from a number of government agencies, particularly from the departments of industry and defence. Universities and research institutes are also active.

CANADIAN PERSPECTIVE

From the international developments described above, it is clear that the major influences on Canada will come from Japan, because of its technology lead, and from the United States, because it is our biggest trading partner. The evidence accumulated in this study on advanced ceramic materials and their market potential leads to five important conclusions that will affect Canadian industry and influence the economic and social well-being of the country.

1) **There is a tremendous opportunity for the existing advanced ceramic industry to grow, not only to satisfy expanding domestic needs, but also to develop export markets.**

   The advanced ceramic industry in Canada is widely based, ranging from ceramic powder manufacturers to primary and secondary manufacturers of components, products and parts. Although most big companies are subsidiaries of multinationals, there are also about 50 medium and small companies that can benefit from the increasing development and use of advanced ceramics.

2) **Advanced ceramics will play a vital supportive role in the growth of high technology industries such as electronics, computers, telecommunications, aerospace, robotics and biotechnology.**

   Canada has prospered in the past primarily because of its natural resources. Now, however, economic pressures are forcing the country to turn to high-tech industries for higher value-added products, lower energy use and more capital-intensive production. Japan has shown that advanced ceramic materials can be pivotal in the growth of existing high-tech industries and products and the creation of new ones. The opportunities are particularly suited to small companies which can find market niches too small to be served by large companies.

3) **Advanced ceramics hold the key to long term solutions to energy and resource industry problems.**

The threats come from two sources. Already, the markets for Canadian resource products are declining because of competition from developing countries with cheaper labour costs. Advanced ceramic materials are expected to take a significant share of the current metal markets, squeezing the resource industries further. However, there are opportunities for these industries to supply higher value-added raw materials to supply the growing advanced ceramic industry throughout the world. The abundant and relatively cheap energy in Canada is a valuable advantage that could be exploited to strengthen international competitiveness.

4) **Advanced ceramics will significantly improve productivity in many manufacturing industries.**

Improved cutting tools are expected to increase productivity by 100 to 200 per cent. Canada's cutting tool industry (about 10 companies) could participate in the development of advanced ceramic tools. Also, better wear- and corrosion-resistant components and products should greatly improve productivity by reducing the down time of machinery and equipment.

5) **As in the United States, Japan and Europe, advanced ceramics offer an opportunity for growth and diversification in other industries.**

Companies in the textile, chemical, metals, processing and assembly sectors can benefit from a diversification into supplying advanced ceramic materials as components or finished products. Auto parts manufacturers are in a particularly advantageous position because of the expected increase in the use of ceramic parts, components and systems in their industry.

Canada is well-placed to take advantage of the coming 'materials' revolution. It already has two necessary assets: a viable advanced ceramic industry base and good R & D. There is considerable expertise among technically trained people in industry, universities, provincial research organizations and federal government laboratories.

This wealth of experience and knowledge is substantial. The team of technically trained people in Canada, while not sufficient to warrant a massive R & D program, is adequate to sustain a well-balanced activity in selected areas. The real question facing Canada today is one of leadership and commitment. The question is not whether Canada **should** invest in the development of an advanced ceramics industry; it is whether Canada can afford **not** to.

OPPORTUNITIES, BARRIERS AND OPTIONS

Opportunities

Canadian industry can break into world markets for advanced ceramics by taking advantage of certain specific opportunities:

° Advanced functional ceramics, particularly electronic ceramics, integrated and fibre optics, sensors and medical implant ceramics;

° Advanced structural ceramics for non-engine applications, particularly for industrial applications, cutting tools and consumer and leisure products;

° Advanced structural ceramics for engine and related applications.

The most immediate business openings are in advanced functional ceramics and advanced structural ceramics for non-engine applications. The market is well established for advanced functional ceramics and the projected annual growth rate for the next two decades exceeds 15 per cent. More important, because there is already considerable industry and a good R & D base, future developments can be made soon and at a relatively low cost. Several large multinational companies are involved in this field and market forces should bring further expansion. Advanced functional ceramics provides excellent opportunities, both existing and emerging, for small Canadian enterprises.

The market for advanced structural ceramics in non-engine applications is more diverse and requires innovative approaches for successful commercialization. It is a rapidly expanding area, however, because materials substitution for existing applications is providing cost/performance advantages. Again, this is a field most suitable for small businesses. However, large companies in the chemical, steel, aluminum, textile and other manufacturing industries may find it worthwhile to invest, if only to meet in-house requirements. One exceptionally interesting market area with good short term potential is for cutting tools.

The technological and cost problems facing commercialization of advanced structural ceramics for engine applications are immense. This has caused the North American auto manufacturers to adopt a wait-and-see attitude although they likely will respond quickly if the Japanese begin to come up with solutions. Market penetration and development, therefore, will take time - at least five years. Competition from the companies which have invested in R & D in this area for almost a decade will be intense. Hence, opportunities for Canadian industry in this area are considered poor in the near term. In the medium term (5 to 10 years) and beyond, the market should be substantial. In any case, this business area is suitable only for companies large enough to sustain substantial long-term investments, particularly those firms that have an already existing relationship with auto manufacturers.

Abundant raw materials and relatively low-cost energy provide unique opportunities for existing ceramic powder manufacturers to expand and for new firms to enter this field, particularly chemical companies. The future for Canada in this area is particularly bright for three reasons.

First, the need for low-cost, reliable sources of ceramic powders is urgent to reduce the overall manufacturing costs of advanced ceramics. Second, Canada can leap-frog in technology development through innovative R & D or technology transfer. Third, and most important, the number of committed powder suppliers is relatively small. There is plenty of room for Canadian suppliers to find a niche in this growing market.

Barriers

Certain barriers have to be overcome to successfully take advantage of the opportunities described above. The most important are:

- Developing or acquiring technology;
- Motivating multinational companies to expand or to create new enterprises;
- Assisting small companies, particularly in market development;
- Finding the required technical personnel.

Technology is perhaps the biggest barrier. To date, almost all the technology developed elsewhere is protected by patents. Therefore, as a first step technology transfer by licencing agreement is the best route to follow. With limited resources, both financial and human, Canada cannot afford to embark on a basic R & D program. Rather, specific business opportunities should be identified and developed.

Although Canada has a relatively good R & D base in universities, provincial research organizations and federal government laboratories, there is no program of long term national objectives. This does not seriously affect multinationals and large Canadian companies because they have access to technology from the parent companies or through licensing agreements. However, smaller companies that could benefit considerably, are adversely affected.

The small size of the Canadian domestic market for advanced ceramics, compared with those in the United States and Japan, may discourage multinationals from investing in Canada. On the other hand, the Canada-US Auto Pact, the defence procurement agreement with the US, relatively low labour costs and the availability of abundant energy at low cost provide good reasons for these companies to invest in Canada.

Almost all the small companies consulted as part of this study indicated that identifying markets is relatively easy, but that developing them is not - because of the expense. They need financial assistance programs to develop and penetrate the markets.

Technical personnel is another serious barrier. At present only one one university - McMaster - graduates ceramic engineers. There should be other methods of increasing the supply of qualified people to support industry and R & D organizations.

Queen's University has just started the Advanced Materials Technology Unit to promote industrial R & D in co-operation with industry and government. Similar joint activities should be promoted.

The Government of Ontario announced, in early 1985, the creation of the Centre for the Commercialization of Advanced Industrial Materials (including advanced ceramics) at the Ontario Research Foundation at a cost of CDN $ 10 million over three years. This is part of the Enterprise Ontario Program and comes as welcome news for the industries of Ontario.

Options

Canada has three broad options to strengthen advanced ceramics activities nationally, both in the manufacturing sectors and in public and private R & D organizations:

- It can seek to accommodate the special needs of the advanced ceramics sector within existing assistance programs;
- It can move deliberately towards expanding existing programs by adding special provisions;
- It can recognize the importance of advanced ceramics for the socio-economic well-being of Canada, and adopt programs similar to those in the United States, Japan, West Germany, Sweden and the United Kingdom.

This last option is the preferred one. Its basic aim would be to gradually lessen the vulnerability of the Canadian economy to developments in the United States and Japan. It would also take advantage of the opportunities to assist Canadian industry, particularly small businesses, existing and emerging. The policies and programs adopted by MITI in Japan, particularly the 'catalytic' role to promote industrial commitment, are acclaimed as the best in the world. They could serve as a model in identifying and implementing the most appropriate policies and programs for Canada. Typically, the Government of Canada could take on the job of leadership and co-ordination to:

- Identify and establish a national program with specific technical objectives to meet industrial and business needs;
- Support and co-ordinate the activities of the federal government laboratories in carrying out the national program.
- Use universities and provincial research organizations to support the established national objectives to assist industry.

Finally, a joint council with representatives from industry, government and universities could be set up as an advisory body to identify and recommend goals for the national program.

1. INTRODUCTION

A quiet revolution is taking place in the development and use of advanced materials in general, and advanced ceramics in particular. The revolution in advanced ceramics began more than a decade ago to satisfy the requirements of industry for materials with superior mechanical, electrical, chemical and thermal properties to meet technological advances in products and processes, better performance, cost and reliability in service. By far the most significant and successful achievements to date have taken place in the development and commercialization of electronic ceramic materials. Japan has achieved supremacy in this market and supplies almost 70 percent of the world demand.

Scientific and technological developments have demonstrated not only the technical feasibility, but also the potential economic, social and environmental benefits that could be gained by using other types of advanced ceramics. Applications include automobile engine components; cutting tools; wear- and corrosion-resistant parts; and heat exchangers. For example, ceramic auto engine components provide three important advantages: improved energy efficiency; reduced toxic emissions; and lower costs, attributable to the use of raw materials which occur abundantly in nature. Ceramic cutting tools offer improved productivity because they can be operated at much higher cutting speeds compared with conventional tools. Wear and corrosion of present-day metallic materials are estimated to cost more than $10 billion per year. This money can be saved by using advanced ceramics.

There is intense world-wide competition to develop and commercialize advanced ceramic components for various applications. The countries that have established national strategies and committed significant resources and investments are: United States, Japan, West Germany and Sweden. The United Kingdom, France and Italy are also active in this area; the UK is expected to make a national commitment soon. These commitments can be attributed to two forces: the need of high-tech industries for new materials without which many technological advances will be impossible, and the huge global market, estimated to be about $20 billion by the year 2000.

Industrial achievements so far are very promising and encouraging. Significant advances have been made in material development for engineering and related applications. Optimism prevails towards finding satisfactory and timely solutions to the remaining technological barriers: reproducibility in manufacturing, reliability in service and competitive cost.

Advanced ceramics are expected to have, in the medium and long term, significant impact on traditional Canadian industrial material suppliers. Some sectors of the Canadian industry might be rejuvenated by using advanced ceramics. Also, new markets could be created for Canadian raw materials required to manufacture advanced ceramics.

The objective of this study is to identify, review and assess the threats and opportunities facing Canadian industry in the field of advanced ceramics.

2. METHODOLOGY

The results reported in this study are based on a review and assessment of information obtained from:

- Published technical literature, private market assessment reports and government publications (listed in the bibliography);
- Information based on in-depth discussions during visits to industry, university laboratories and government research laboratories in the United States, Japan, West Germany, France, Sweden and the UK. Specific data were obtained on ceramic technology status and trends, market outlooks, overall competition and general product economics (Appendix A);
- Personal discussions with selected specialists in Canada (Appendix B).

3. DESCRIPTION OF ADVANCED CERAMICS

3.1 Definition

'Ceramics' - from the Greek word 'keramos' - is a term which encompasses a wide variety of inorganic materials. The present-day definition is broader than the historic one: the art and science of making and using solid articles by the action of heat on earthy raw materials. The current generally accepted definition, adopted originally by the US National Academy of Sciences, is: "an inorganic, non-metallic, material processed or consolidated at high temperatures." In Europe and many other countries 'ceramics' and 'glass' are distinguished from one another, at least by industry. In North America and Japan, however, the term 'ceramics' includes glass.

Today, ceramics can be divided into two groups, traditional and advanced. To the family of traditional ceramics, as shown in Figure 1, belong materials which have been used by the general public (consumer market) primary industries for generations. Typical examples are: pottery, bricks, dinnerware, sanitary ware, insulation (thermal and electrical), glass and refractories.

The term "advanced ceramics"* refers to a broad and diverse group of inorganic materials comprising and combining oxides, carbides, nitrides and graphite. Their distinguishing features, in general, are: a substantially higher level of performance, much more stringent requirements on composition control and processing, and a market value based on unique performance which justifies a much higher cost.

Three routes have been adopted in formulating and developing advance ceramic materials. First, by using new concepts of ceramic science and processing, the properties of conventional ceramics have been improved. Second, new material compositions have been developed which inherently possess superior properties. These materials can be processed by old conventional and/or new sophisticated techniques. In either case, they yield ceramics with superior properties. Third, composite technology is used to achieve the desired properties: ceramics-in-ceramics, ceramics-in-metals and metal-in-ceramics techniques are used.

Advanced ceramics are generally used as components in processing equipment, devices or machinery because they can perform some functions better than competing metals or polymers.

---

* In North America and Europe the term "advanced ceramics" denotes high-performance ceramics with superior electrical, mechanical, chemical or thermal properties. In Japan, however, the term "fine ceramics" is used because these materials are made from very fine powders and their microstructure consists of fine-grained crystals.

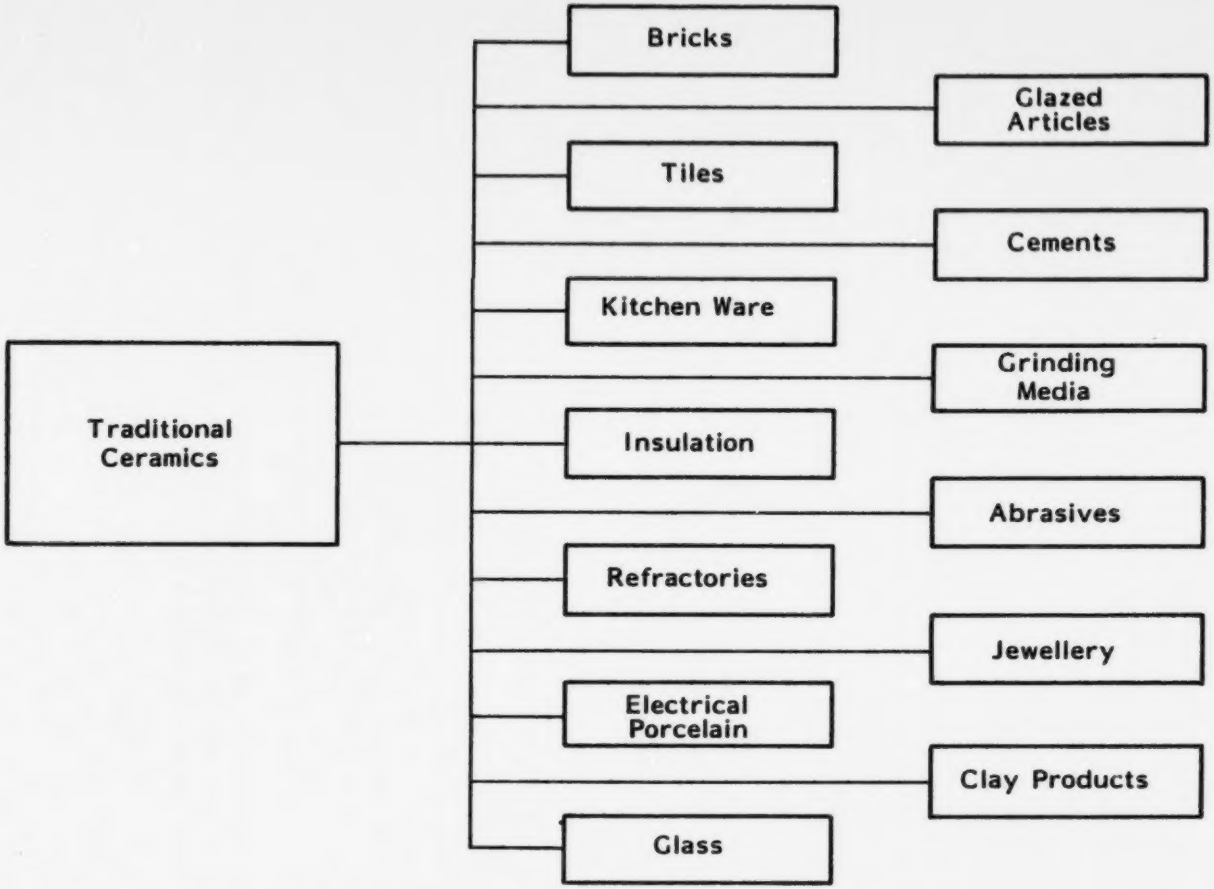

Traditional Ceramics
Bricks
Glazed Articles
Tiles
Cements
Kitchen Ware
Grinding Media
Insulation
Abrasives
Refractories
Jewellery
Electrical Porcelain
Clay Products
Glass

FIGURE 1: Scope of Traditional Ceramics

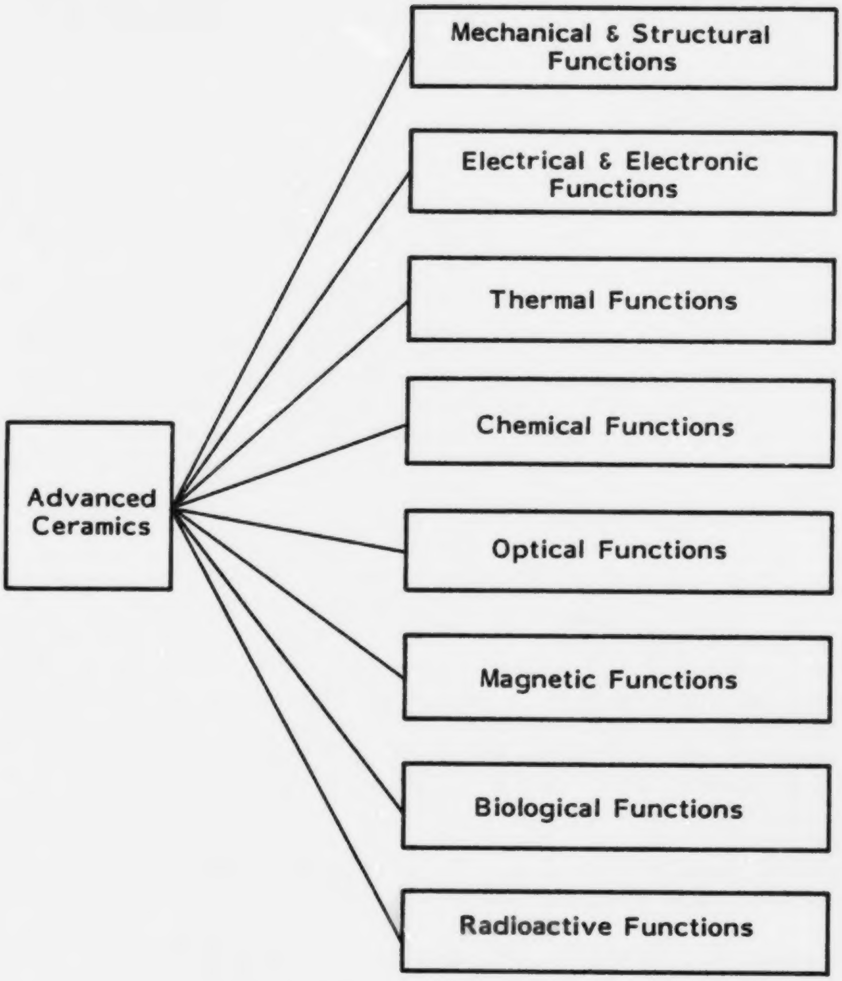

Advanced Ceramics
Mechanical & Structural Functions
Electrical & Electronic Functions
Thermal Functions
Chemical Functions
Optical Functions
Magnetic Functions
Biological Functions
Radioactive Functions

FIGURE 2: Functional Scope of Advanced Ceramics (Modified from Kenney and Bowen Data)

In developing and using advanced ceramics it is necessary to take into consideration the functional properties required to meet the specific end use. The wide spectrum of functional properties satisfied by these materials is shown in Figure 2. The unique properties of advanced ceramics which make them specially useful for high performance applications are listed below:

- ° High Degree of Hardness
- ° High Temperature Mechanical Strength
- ° High Corrosion and Erosion Resistance
- ° High Piezoelectric Coupling Coefficient
- ° High Magnetic Permeability
- ° High Melting Point
- ° Low Density
- ° Optical Transparency
- ° Fast Ion Conduction
- ° Low Thermal Conductivity

To capitalize on these superior properties, however, substantial research and development remains to be done to overcome the limitations imposed by their negative properties, primarily their extreme brittleness. The lack of plasticity is the major complicating feature in their design, processing and use. The brittle property has two major effects: ceramics cannot be deformed after shaping as can metals (e.g., forging); and second, failure of ceramics is usually sudden and catastrophic.

3.2 Classification and Scope

A system of classification for advanced ceramics adopted by the Fine Ceramics Office, Ministry of International Trade and Industry, Toyko, Japan, is given in Figure 3. More detailed interrelationships between function, property and applications are given in Figures 4 to 8. From these it is evident that advanced ceramics have many uses encompassing several industrial sectors: transportation, electronics, communications, manufacturing and energy. Due to diversity of the applications, even a moderate penetration of advanced ceramics is expected to similarly affect most industries.

A broader characterization in widespread use today classifies all applications into either structural ceramics or functional ceramics.

The 'structural' category consists primarily of the mechanical functions, but also includes the chemical and thermal aspects (e.g., corrosion resistance, thermal shock resistance) when these are necessary to carry out the mechanical function. The 'functional' category takes in all the electric, magnetic, optical, biological and nuclear functions, plus the chemical functions which involve the direct use of the relevant properties.

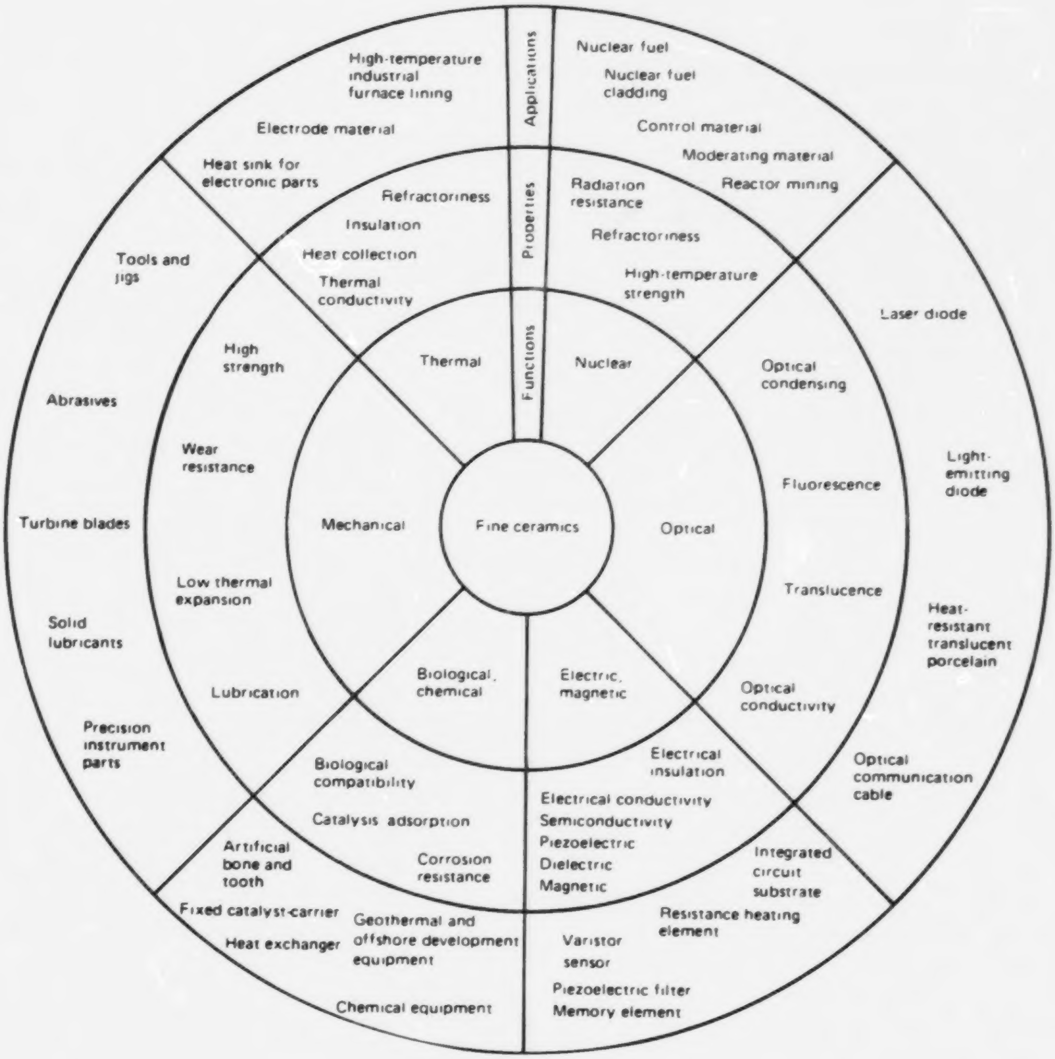

Applications
Properties
Functions
Fine ceramics
Thermal
Nuclear
Optical
Electric, magnetic
Biological, chemical
Mechanical
Refractoriness
Insulation
Heat collection
Thermal conductivity
Radiation resistance
Refractoriness
High-temperature strength
Optical condensing
Fluorescence
Translucence
Optical conductivity
Electrical insulation
Electrical conductivity
Semiconductivity
Piezoelectric
Dielectric
Magnetic
Biological compatibility
Catalysis adsorption
Corrosion resistance
High strength
Wear resistance
Low thermal expansion
Lubrication
High-temperature industrial furnace lining
Electrode material
Heat sink for electronic parts
Nuclear fuel
Nuclear fuel cladding
Control material
Moderating material
Reactor mining
Laser diode
Light-emitting diode
Heat-resistant translucent porcelain
Optical communication cable
Integrated circuit substrate
Resistance heating element
Varistor sensor
Piezoelectric filter
Memory element
Artificial bone and tooth
Fixed catalyst-carrier
Heat exchanger
Geothermal and offshore development equipment
Chemical equipment
Tools and jigs
Abrasives
Turbine blades
Solid lubricants
Precision instrument parts

FIGURE 3: Functional Applications of Advanced Ceramics
(Source: Fine Ceramics Office, MITI, Tokyo)

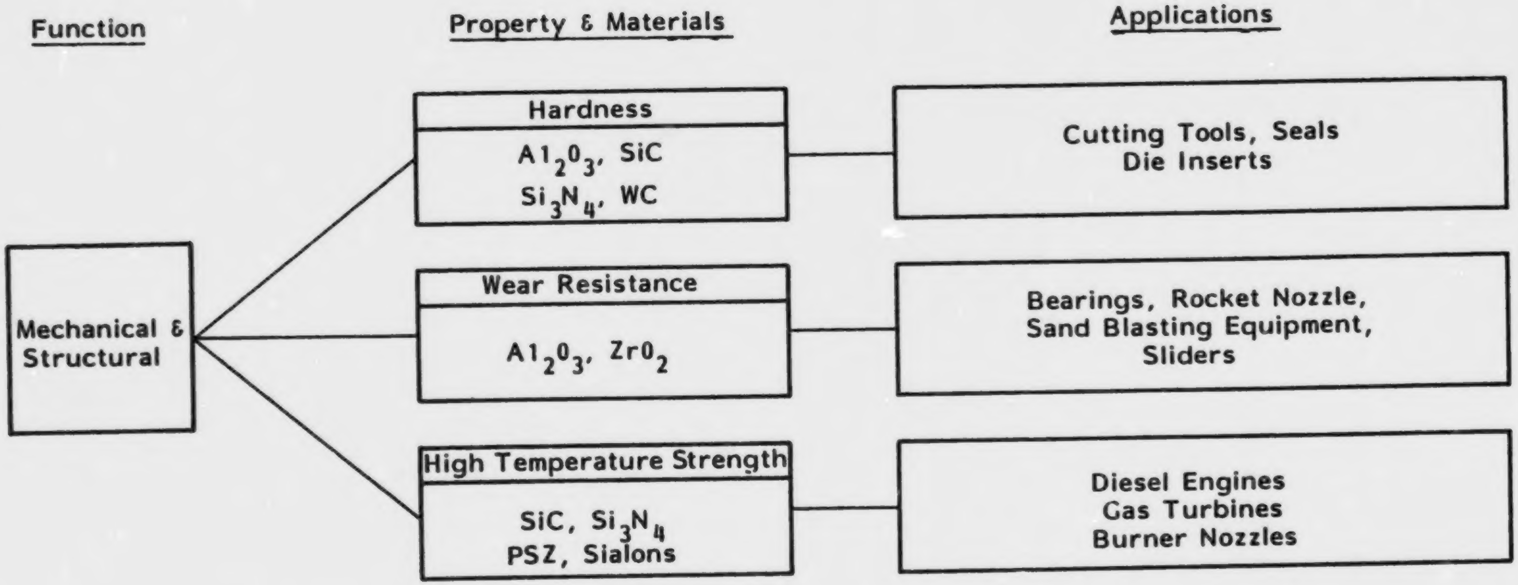

Function
Property & Materials
Applications
Mechanical & Structural
Hardness
Al_2O_3, SiC
Si_3N_4, WC
Wear Resistance
Al_2O_3, ZrO_2
High Temperature Strength
SiC, Si_3N_4
PSZ, Sialons
Cutting Tools, Seals
Die Inserts
Bearings, Rocket Nozzle,
Sand Blasting Equipment,
Sliders
Diesel Engines
Gas Turbines
Burner Nozzles

FIGURE 4: Scope of Advanced Ceramics for Mechanical and Structural Applications (after Kenney and Bowen)

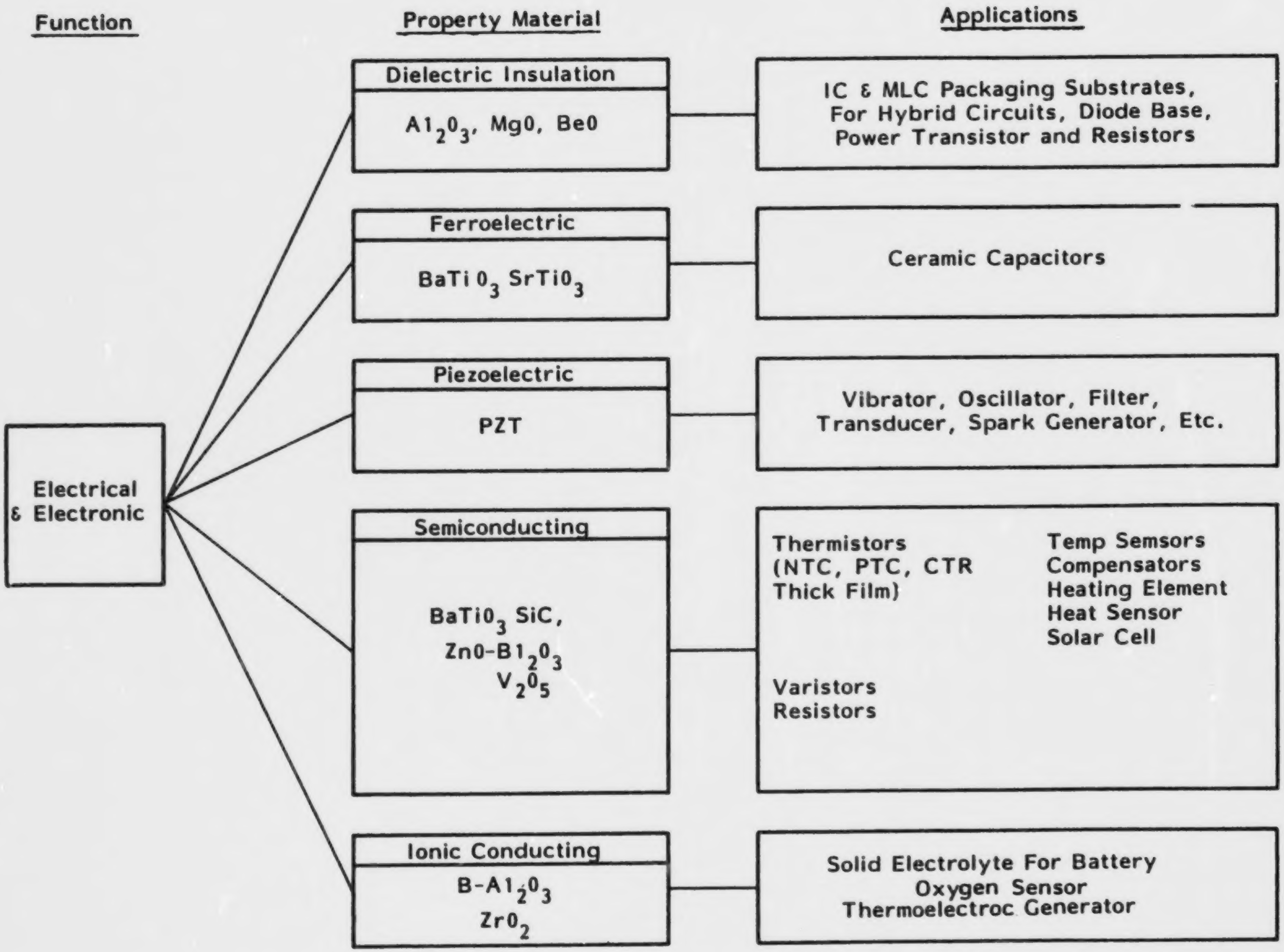

Function
Property Material
Applications
Electrical & Electronic
Dielectric Insulation
$A1_20_3$, Mg0, Be0
IC & MLC Packaging Substrates, For Hybrid Circuits, Diode Base, Power Transistor and Resistors
Ferroelectric
$BaTi0_3$ $SrTi0_3$
Ceramic Capacitors
Piezoelectric
PZT
Vibrator, Oscillator, Filter, Transducer, Spark Generator, Etc.
Semiconducting
$BaTi0_3$ SiC, $Zn0\text{-}B1_20_3$ V_20_5
Thermistors (NTC, PTC, CTR Thick Film)
Varistors
Resistors
Temp Semsors
Compensators
Heating Element
Heat Sensor
Solar Cell
Ionic Conducting
$B\text{-}A1_20_3$
$Zr0_2$
Solid Electrolyte For Battery
Oxygen Sensor
Thermoelectroc Generator

FIGURE 5: Scope of Advanced Ceramics for Electrical and Electronic Applications (after Kenney and Bowen)

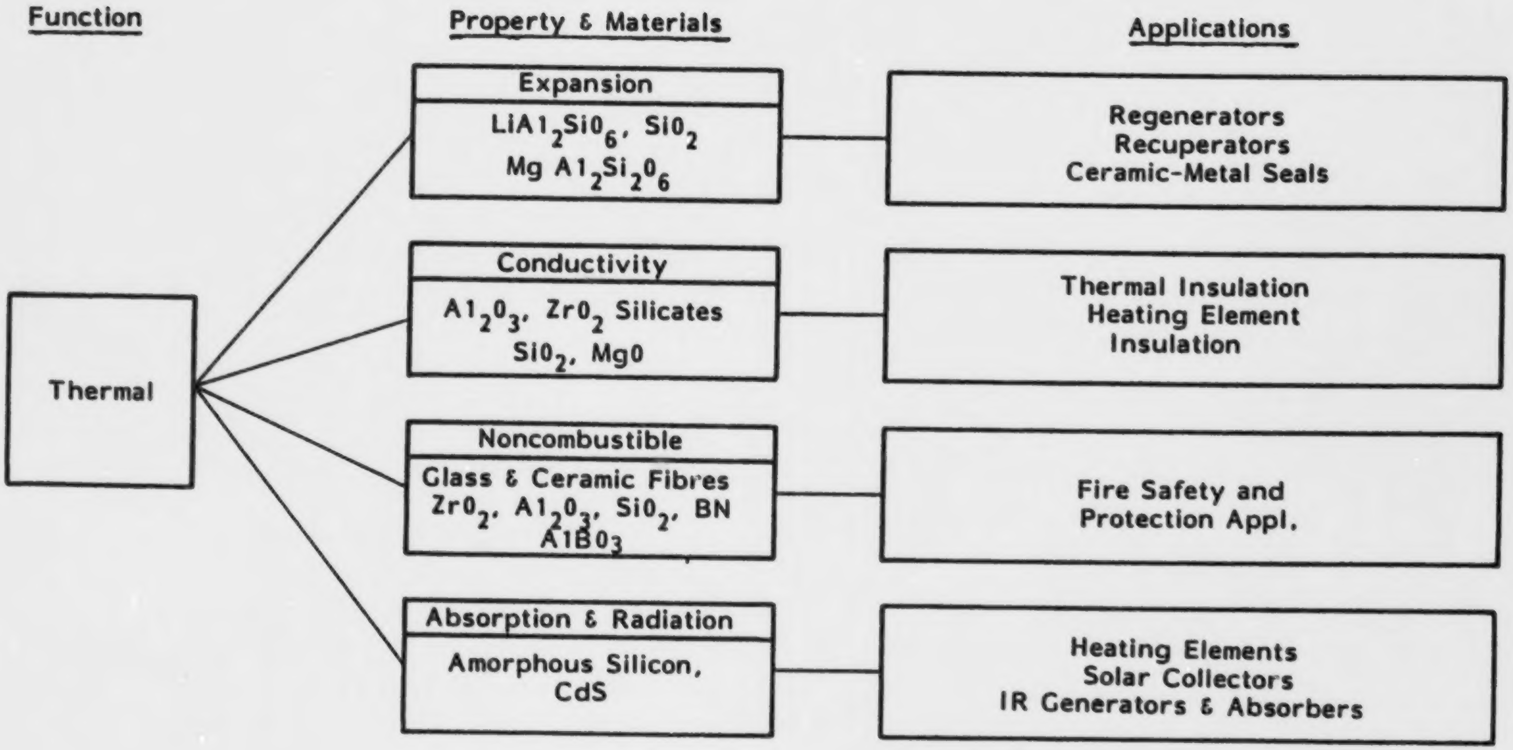

Function
Property & Materials
Applications
Thermal
Expansion
$LiAl_2SiO_6$, SiO_2
$Mg\ Al_2Si_2O_6$
Conductivity
Al_2O_3, ZrO_2 Silicates
SiO_2, MgO
Noncombustible
Glass & Ceramic Fibres
ZrO_2, Al_2O_3, SiO_2, BN
$AlBO_3$
Absorption & Radiation
Amorphous Silicon,
CdS
Regenerators
Recuperators
Ceramic-Metal Seals
Thermal Insulation
Heating Element
Insulation
Fire Safety and
Protection Appl.
Heating Elements
Solar Collectors
IR Generators & Absorbers

FIGURE 6: Scope of Advanced Ceramics for Thermal Applications (after Kenny and Bowen)

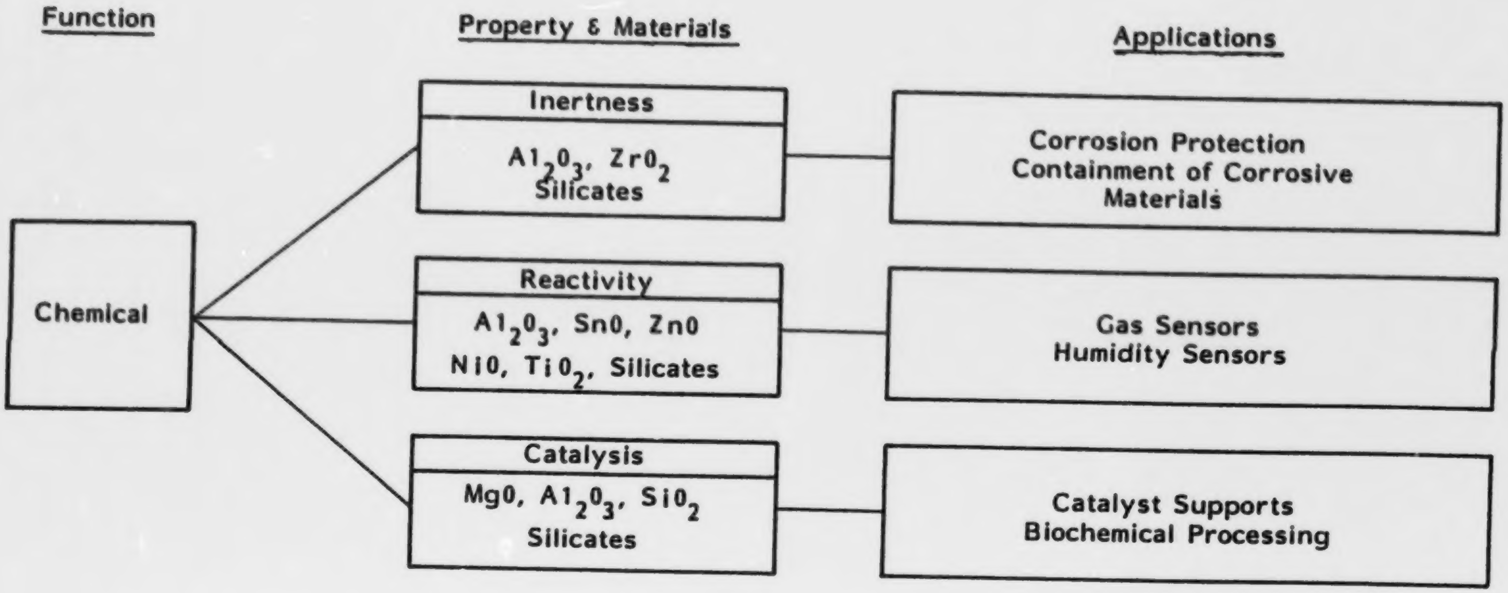

Function
Property & Materials
Applications
Chemical
Inertness
Al_2O_3, ZrO_2
Silicates
Reactivity
Al_2O_3, SnO, ZnO
NiO, TiO_2, Silicates
Catalysis
MgO, Al_2O_3, SiO_2
Silicates
Corrosion Protection
Containment of Corrosive
Materials
Gas Sensors
Humidity Sensors
Catalyst Supports
Biochemical Processing

FIGURE 7: Scope of Advanced Ceramics for Chemical Applications (after Kenney and Bowen)

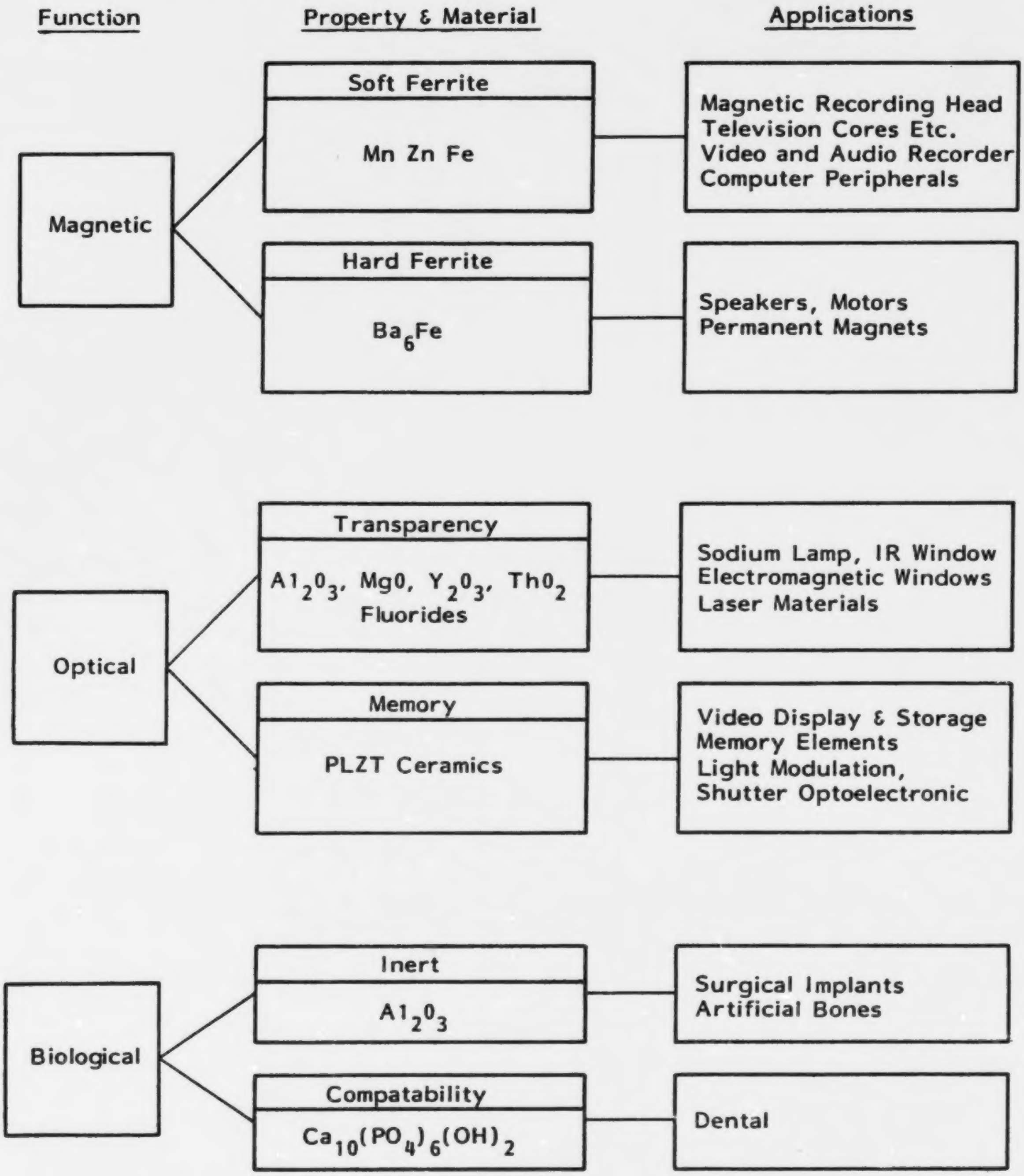

Function
Property & Material
Applications
Magnetic
Soft Ferrite
Mn Zn Fe
Magnetic Recording Head
Television Cores Etc.
Video and Audio Recorder
Computer Peripherals
Hard Ferrite
Ba_6Fe
Speakers, Motors
Permanent Magnets
Optical
Transparency
Al_2O_3, MgO, Y_2O_3, ThO_2
Fluorides
Sodium Lamp, IR Window
Electromagnetic Windows
Laser Materials
Memory
PLZT Ceramics
Video Display & Storage
Memory Elements
Light Modulation,
Shutter Optoelectronic
Biological
Inert
Al_2O_3
Surgical Implants
Artificial Bones
Compatability
$Ca_{10}(PO_4)_6(OH)_2$
Dental

FIGURE 8: Scope of Advanced Ceramics for Magnetic, Optical, and Biological Applications (after Kenny and Bowen)

3.3 Materials and Technology

3.3.1 General

As is to be expected, the chemical composition and crystal structure of advanced ceramic materials vary widely. For any given application, therefore, it is necessary to identify the specific composition(s) that exhibit the required functional properties. The ultimate properties of the ceramic, however, depend upon its microstructure which, in turn, depends upon process conditions and parameters. Hence, a brief discussion of the interrelationships between microstructure and processes will be presented. Since the properties of the 'structural ceramics' are quite different from the 'functional ceramics', they will be discussed separately.

3.3.2 Ceramic Processing

Figure 9 provides a simplified view of the ceramic production processes. In general, the ceramic raw materials in the form of powders are mixed with the required additives such as binders, defloculents or sintering aids. The mixing can be dry or in a slurry, in which case it is spray-dried. Four techniques are normally used for shaping the ceramic. They are: slip casting using a slurry and a suitable mold material; uniaxial pressing; isostatic pressing; and injection molding. These processes are commonly used in the manufacture of traditional ceramics and, with modifications, are also being adapted for advanced ceramics. Slip casting and injection molding are particularly attractive; the former for complex hollow shapes and the latter for the mass production of simple as well as complex shapes. After forming, the articles are dried to obtain 'green' products; in the case of injection molding, the organics have to be burnt off at low temperatures, usually below 500°C. The densification of the green products is done by 'sintering', i.e., by heat treatment at higher temperatures to bring about consolidation of the particles by chemical bonding. The heat treatment conditions, such as sintering temperature, rates of heating and cooling, and sintering times depend upon the chemical composition of the materials as well as the microstructure required.

Hot pressing (HP) and hot-isostatic pressing (HIP) are relatively new processes. They are expensive and, therefore, are used only where the extra cost is justified and can be recovered by the higher selling price of the product. In both these techniques, the shaping of the ceramic and sintering take place simultaneously. By controlling the time-temperature relationships the desired microstructure can be obtained. Both the processes yield very high density materials, a characteristic required of almost all advanced ceramic products. Both these processes are in commercial use. HP techniques can be used only for simple shapes whereas HIP processes can be used for simple and complex shapes such as turbocharger rotors. HIP techniques can be combined with normal sintering technology to achieve defect-free components with superior properties (e.g., magnetic recording heads made of ferrites, piezoelectric ceramics for transducers, cutting tools and turbine blades). The sintering-HIP technologies for producing advanced ceramics

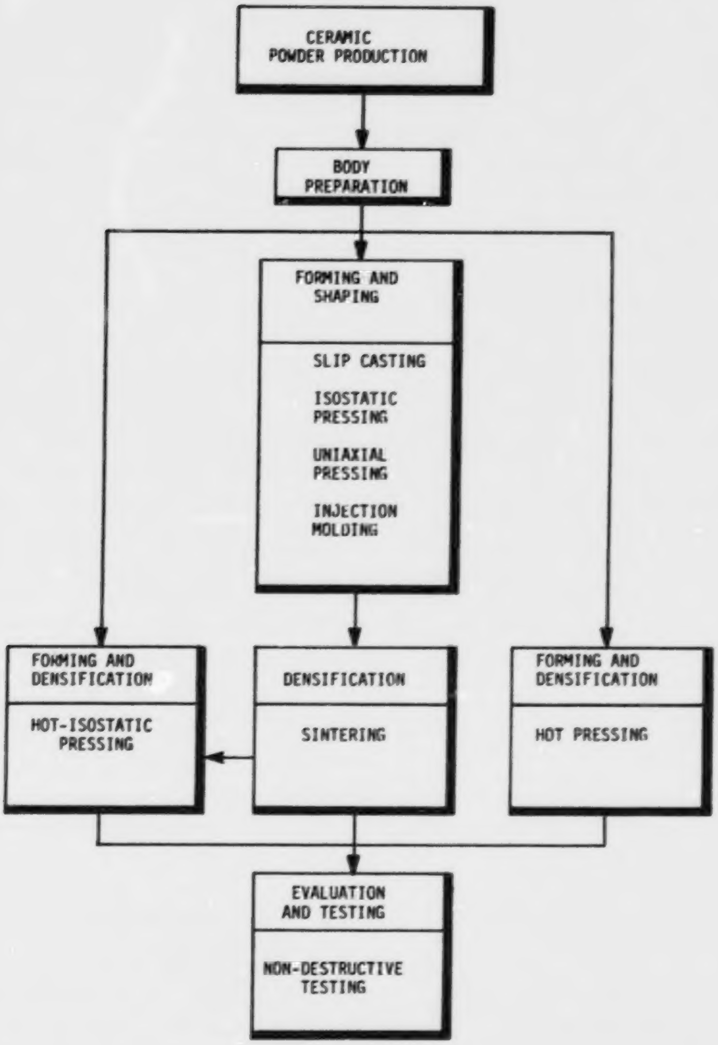

CERAMIC POWDER PRODUCTION
BODY PREPARATION
FORMING AND SHAPING
SLIP CASTING
ISOSTATIC PRESSING
UNIAXIAL PRESSING
INJECTION MOLDING
FORMING AND DENSIFICATION
HOT-ISOSTATIC PRESSING
DENSIFICATION
SINTERING
FORMING AND DENSIFICATION
HOT PRESSING
EVALUATION AND TESTING
NON-DESTRUCTIVE TESTING

FIGURE 9: Ceramic Fabrication Processes

are being developed actively in the USA (General Electric Co., GTE, Gorham, Garret, Batelle), Sweden (AESA Ceram), and Japan (Kobe Steel, Mitsubishi).

The sintering-HIP technology being developed by Kobe Steel in Japan shows considerable promise for reducing the manufacturing cost. By a novel design, the sintered products can be transferred into the HIP furnace from the sintering furnace without cooling; this new process is expected to cut the heat treatment time by more than 50 percent.

The ASEA Ceram HIP process, developed in Sweden, is also unique and is said to possess features suitable for mass production at reasonable cost. This process is now available for licencing. In the USA, the Norton Company has acquired the technology. The process is shown in Figure 10.

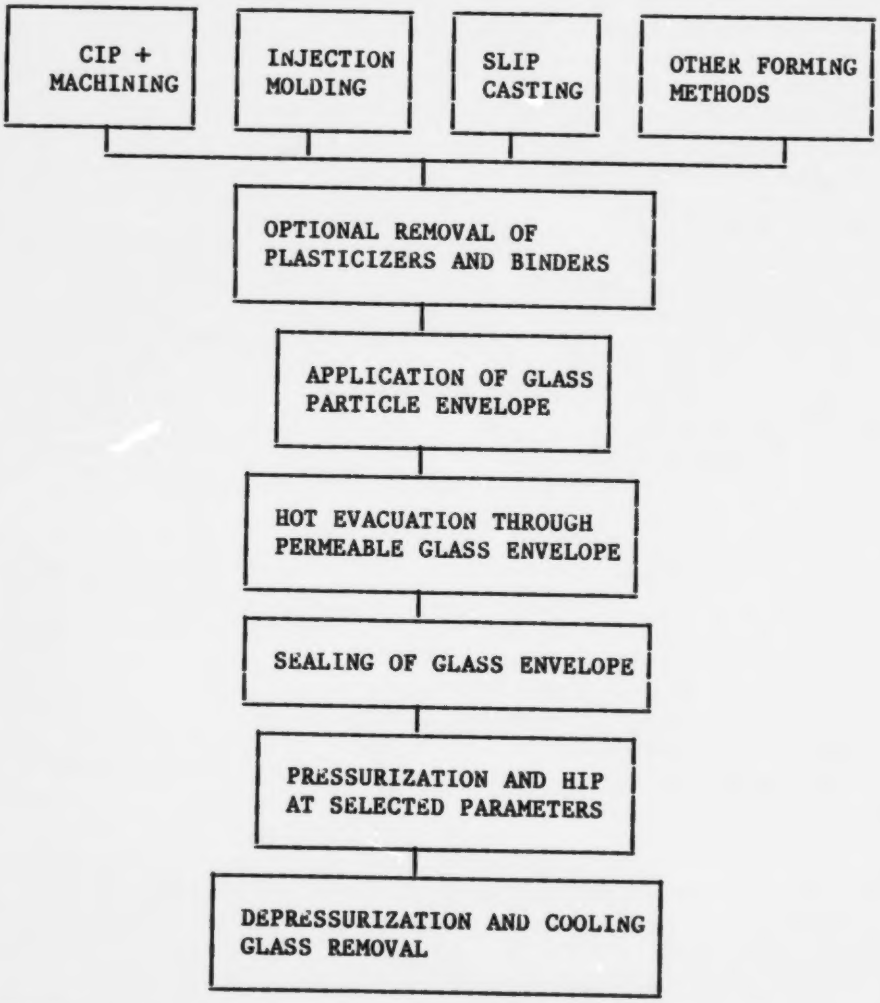

CIP + MACHINING
INJECTION MOLDING
SLIP CASTING
OTHER FORMING METHODS
OPTIONAL REMOVAL OF PLASTICIZERS AND BINDERS
APPLICATION OF GLASS PARTICLE ENVELOPE
HOT EVACUATION THROUGH PERMEABLE GLASS ENVELOPE
SEALING OF GLASS ENVELOPE
PRESSURIZATION AND HIP AT SELECTED PARAMETERS
DEPRESSURIZATION AND COOLING GLASS REMOVAL

FIGURE 10: ASEA Ceram Hot Isostatic Pressing Process

It is now universally recognized that reproducibility in manufacturing and reliability of properties of advanced ceramics can be achieved only through a better understanding of, and improvement in, ceramic processing. Two types of technological barriers have been identified. They are:

- Starting Material Barriers
- Process Barriers

Starting Material Barriers

In general all ceramic fabrication processes depend upon the characteristics and properties of the starting powders. There are three key technological barriers to, or opportunities for technological change, at the ceramic powder stage. First, powders need to have improved characterization of their physical, chemical and surface properties. Better characterization of bulk and surface chemistry, particle size distribution, particle shape, surface area, and agglomerate structure are required. Second, the relationships between powder characteristics, process parameters and final products are not well established now and need to be addressed. Third, it is projected that improved powders will help ensure the successful completion of succeeding processing steps. Ceramic powders tend to contain agglomerates or clusters of particles that adhere to each other. When uncorrected, agglomerates can cause flaws in the ceramic and the size of the agglomerate is directly related to the size of the microstructural defect in the final product.

One school of thought in the ceramics community subscribes to the view that the key to solving the cost and reliability problems of advanced ceramics lies in producing ultrafine, monodisperse, spherically shaped powders that are free of agglomerates. Among the powder processing techniques being considered by these advocates of spherical monodisperse powders are sol-gel technology, polymer technology, and gas phase reactions.

Another school of material scientists who agree that agglomerates indeed are detrimental to final properties, believes that there is insufficient evidence to support the advantages to be achieved by the use of spherical, monodisperse powders. In fact, it is pointed out that the use of such powders may not even be necessary, let alone sufficient, for producing final products with the desirable properties. There is reason to believe that even by using an ideal powder, numerous other problems can occur during subsequent steps that might introduce flaws.

Process Barriers

Problems and opportunities for improvement have been identified at all stages of the component processing operations. The need for a better understanding of the forming or consolidation step has been clearly identified as desirable, particularly the production of a defect-free green body. The origin of many flaws in the final, densified microstructure has been traced to the imperfections contained in the green body. Slip casting and injection molding techniques are found to be desirable from this point of view. Slip casting starts out with a colloidal dispersion of powder in fluids, and injection molding produces shear within the powder-binder mix that breaks up agglomerates.

Also associated with the technological challenge of eliminating green body defects are the following problems, currently being addressed:

- Uniform packing of powders without density (or porosity) variations, linked to forming methods that do not promote agglomeration.

- The effects and mechanism of binder removal are critical to defect density. It currently takes about four to five days for the burnout cycle. Fluid removal in the slip casting process also takes a relatively long time. Work is in progress to reduce the time cycle.

Technical problems are also associated with the sintering cycle, e.g., densifications have been identified and are being addressed.

3.3.3 Advanced Structural Ceramics

The advanced structural ceramic materials that have been identified as suitable for engineering applications are:

- Silicon Nitride, Si_3N_4
- Sialon, $Si_{6-x}Al_xN_{8-x}O_x$
- Silicon Carbide, SiC
- Zirconia (PSZ), ZrO_2

These materials have been under development for over 15 years and the first generation compositions have reached the commercial production stage for a number of applications. Their properties are compared in Table 1. For engine applications, however, the material compositions currently available, as well as the process technologies, are not entirely satisfactory. The most significant limitations of these applications are non-reproducibility in manufacturing and lack of reliability in the properties. As a result, intense R & D efforts are being carried out both for composition optimization and for the improvement of process technologies. The status of work on these materials will be briefly described.

TABLE 1

Properties of Advanced Structural Ceramics

Material	Strength	Toughness	Thermal Expansion
	MPa	MPamexp (1/2)	10exp(-6)/C
	Types of Silicon Nitride		
RBSN	300	3.6	3.3
HPSN	1100	6.6	3.5
GPSSN	440	2.9	3.5
	Types of Silicon Carbide		
Alpha SSC	420	2 to 3	4.1
Beta SSC	533	2.4	4.1
HPSC	880	3.9	4.2
	Types of Transformation-Toughened Ceramics		
PSZ	700+	8+	10.2
TTA	900	8	7
	Ceramic-Ceramic Composites		
SiC-LAS	620	15	1 to 4

Key:

RBSN	Reaction-bonded silicon nitride
HPSN	Hot-pressed silicon nitride
GPSSN	Gas pressure sintered silicon nitride
Alpha SSC	Alpha-phase sintered silicon carbide
Beta SSC	Beta-phase sintered silicon carbide
HPSC	Hot-pressed silicon carbide
PSZ	Partially stabilized zirconia
TTA	Transformation-toughened alumina
SiC-LAS	Silicon carbide fibres in lithium aluminosilicate glass

3.3.3.1 Silicon Nitride (Si_3N_4)

General

Silicon nitride was first discovered in 1910 but it was not until the 1960s that commercial interest widened because of technological developments in the UK, leading to high-strength compositions. The possibility of a wide range of applications became apparent and the development of the technology accelerated during the 1970s as various projects started in the USA, West Germany and Japan.

Production of Powder

The engineering properties of silicon nitride ceramic components depend heavily on the nature, structure and properties of the starting powder. Effective sintering, in particular, will place stringent requirements on the starting powder purity and characteristics. The specific surface area and oxygen content of the powders are particularly important from the point of view of obtaining good properties in the finished product. The specific surface area and oxygen content of the commercially available materials are compared in Figure 11.

Some of the important requirements are:

- High specific surface area (25 m^2/g)
- High α -phase and controlled β -phase
- Low metallic and carbon contamination
- Controlled oxygen and non-metallic content

Silicon nitride powders can be manufactured by a number of methods. However, the following four methods are of commercial importance.

(i) Nitridation of Silicon Powder

In this process, metallic silicon powder is reacted with pure nitrogen or gas mixtures such as $H_2 + N_2$ or ammonia. At temperatures below 1450°C, predominantly α -phase silicon nitride is produced which has to be milled to achieve fine powders. Some of the companies using this process commercially are listed in Figure 11. It is estimated that H. C. Starck Co. in West Germany produces about 50 tons/year.

(ii) Carbothermic Reduction of Silica

In the presence of carbon and nitrogen, fine grained silica reacts according to the following equation:

$$3\ SiO_2 + 6C + 2\ N_2 \longrightarrow Si_3N_4 + 6\ CO$$

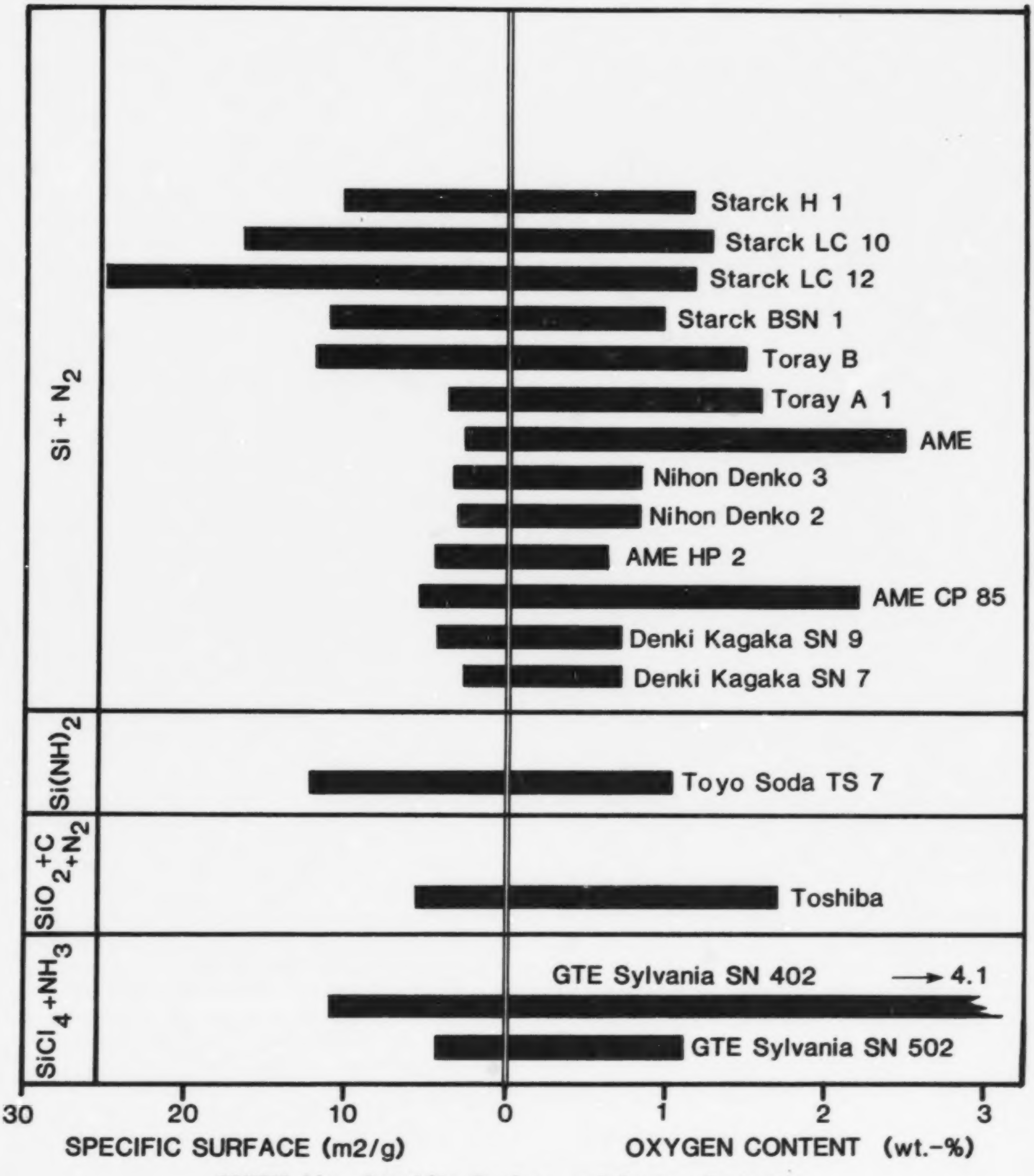


FIGURE 11: Specific Surface and Oxygen Content of Commercial Silicon Nitride Powders

Source: Dr. Grill, Max Planck Institute, Stuttgart, West Germany

This process is used by Toshiba Corporation in Japan. The present cost is estimated to be about Y20,000/kg (US$ 80/kg). The goal is to reduce the cost to about Y5,000/kg. Since excess carbon is used in the production, some free carbon remains in the nitride powder. By annealing in air this carbon is partially oxidized. Seeding the silica powder with small amounts of preformed silicon nitride powder yields a very consistent equiaxed α -silicon nitride powder with good flow and packing characteristics.

(iii) Vapour Phase Reaction

Silicon nitride powder can also be prepared through the reaction of gaseous silicon compounds such as silicon tetrachloride or silane with ammonia.

$$3\ SiCl_4 + 4\ NH_3 \longrightarrow Si_3N_4 + 12\ HCl$$

Using the correct reaction conditions, very fine amorphous silicon nitride powder can be produced directly. Contamination of the powder by chlorine, which affects the properties of the components after hot pressing, is a problem. GTE Sylvania in the USA is using this process for commercial production. Although GTE initially was marketing the powders, it is now using the process for in-house production of cutting tools.

Recent interest in this area has been concerned with the use of laser energy for molecular excitation and reaction leading to the formation of very fine (50 nm) high purity powders. These are normally amorphous but crystallize at about 1300°C into the α -phase. This process is currently in the laboratory stage at Rutgers University in the USA.

(iv) Decomposition of Silicon Imide

High-quality silicon nitride powder (α -variety) can also be produced by the decomposition of silicon imide.

$$3\ Si(NH)_2 \longrightarrow Si_3N_4 + 2\ NH_3$$

This process is being commercially used by two companies in Japan, Toyo Soda and Ube Industries. Ube Industries is now building a new manufacturing facility and the production will increase to 100 tons/year. The plant is expected to be ready by 1986.

Fabrication of Silicon Nitride Ceramic Components

The process techniques used in the manufacture of silicon nitride components depend upon the ultimate properties desired and the specific use of the component. The following materials - listed in sequence of their historic development - are produced by different processes:

Reaction-bonded silicon nitride	RBSN
Pressure sintered, hot-pressed, and hot-isostatically pressed silicon nitride	PSSN, HPSN, HIPSN
Sintered silicon nitride	SSN
Post-sintered reaction-bonded silicon nitride	PSSN, HPSN, HIPSN

Reaction-bonded silicon nitride (RBSN) is produced in one of the following four ways:

- By partially nitriding an isostatically pressed shape of finely divided silicon powder, machining to shape, and then fully nitriding in a nitrogen atmosphere.
- Casting a shape of silicon powder slurry, drawing off the liquid, drying and nitriding.
- Cold die pressing a shape which is then nitrided - a particularly useful technique for producing large quantities of simple shape.
- Injection molding of fine silicon powder, followed by burnoff of binder and nitriding.

These four methods are used commercially. For example, two companies in the UK (Advanced Materials Engineering Ltd. and AE Developments Ltd.), have been commercially manufacturing these products for a number of years. The latter company markets its products under the trade name NITRASIL.

Pressure sintered silicon nitride (PSSN) is produced from silicon nitride powder. The powder is shaped to the green body by any of the forming tecnhiques. It is then sintered under a high pressure of nitrogen to prevent volatilization of nitrogen and silicon at high sintering temperatures ($>$1600°C). This method is not commercially used.

In the hot-press (HP) and hot-isostatic press (HIP) techniques, the starting material is silicon nitride powder. In the former, the powder is mixed with suitable sintering aids to reduce the sintering temperature; the shaping and sintering take place during the hot-pressing process. In the HIP process, the silicon nitride powder is preshaped by any of the shaping processes (usually injection molding technique), and sintered in the HIP furnace. This method can also be used to eliminate microstructural defects from products made by other processes.

In the sintered silicon nitride (SSN) process, the silicon nitride powder is mixed with the required amounts of sintering aids (yttrium oxide, Y_2O_3, is the preferred material), fabricated to the desired shape, and sintered in nitrogen at one atmosphere pressure of nitrogen.

The post-sintered reaction-bonded (PSRBSN) process is used to improve the properties of the product made by the RBSN process.

Technology Status and Trends

Although there is some divergence of opinion in the technical community, the consensus appears to be that silicon nitride will be accepted as the preferred material, but not necessarily for all applications. There are problem areas still to be solved:

- Commercial production of well-characterized silicon nitride powder. Reliability of properties and low cost (US$ 20/kg) are necessary.
- Development of process technologies to manufacture the components reproducibly and with reliable properties. Of particular importance is the reduction in manufacturing cost by near-net shape techniques to eliminate the costly finishing step.
- Development of non-destructive testing is essential for commercial acceptance of the components.
- Elimination of design methodology barriers. Ceramic materials require design criteria and techniques which differ markedly from those employed with metals. As a result, metal parts cannot simply be replaced by ceramics without system redesign.

The foregoing apply equally to the other materials, silicon carbide, sialon and zirconia. The scope of scientific and technological studies currently under way to commercialize advanced ceramics is given in Figure 11.

3.3.3.2 Sialon $S_{6-x}Al_xN_{8-x}O_x$

The sialons were discovered independently in the early 1970s by research workers in the UK and in Japan. In the UK the discovery took place at the Wolfson Research Centre for High-Strength Materials, University of Newcastle-Upon-Tyne, from work supported by Joseph Lucas Ltd. and the Wolfson Foundation. In Japan, the discovery was made by the Toshiba Corporation and Toyota Motor Company.

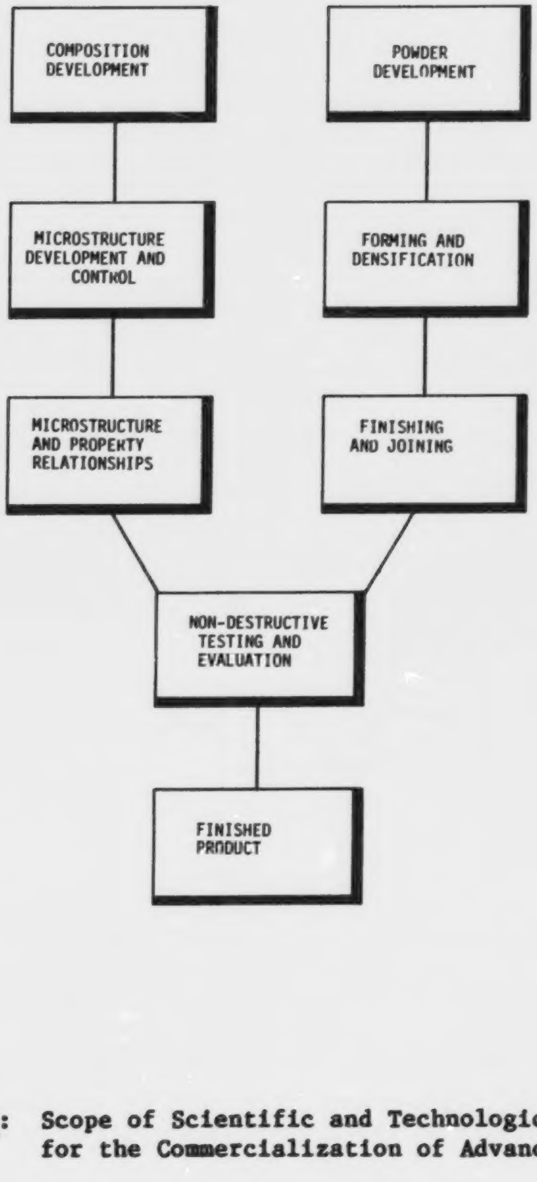

COMPOSITION DEVELOPMENT
POWDER DEVELOPMENT
MICROSTRUCTURE DEVELOPMENT AND CONTROL
FORMING AND DENSIFICATION
MICROSTRUCTURE AND PROPERTY RELATIONSHIPS
FINISHING AND JOINING
NON-DESTRUCTIVE TESTING AND EVALUATION
FINISHED PRODUCT

FIGURE 12: **Scope of Scientific and Technological Studies for the Commercialization of Advanced Ceramics**

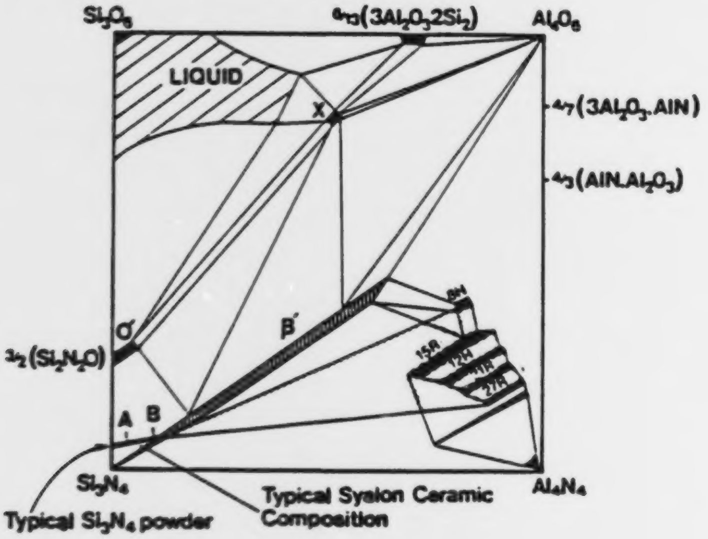
The sialon compositions can be represented by the formula:

$$Si_{6-x}Al_xN_{8-x}O_x$$

(where 'x' denotes the number of nitrogen atoms substituted by oxygen atoms).

The degree of substitution can be varied to produce a variety of materials with a wide range of properties. The maximum value for 'x' is 4.2.

Sialons are synthesized by reacting together the appropriate amounts of silicon nitride, silica, alumina and aluminum nitride to give the compositions shown in the diagram below:


Si₃O₆
6/13(3Al₂O₃.2Si₂)
Al₄O₆
LIQUID
X
4/7(3Al₂O₃.AlN)
4/3(AlN.Al₂O₃)
O′
3/2(Si₂N₂O)
β′
8H
15R
12H
21R
27R
A
B
Si₃N₄
Al₄N₄
Typical Syalon Ceramic Composition
Typical Si₃N₄ powder

Source: Reference, Bibliography page 164

The Lucas patented method involves the use of high α - phase silicon nitride powder, mixed with aluminum oxide, polytype, and yttrium oxide, which acts as a liquid phase sintering aid. A range of useful sialon compositions can be produced yielding a variety of microstructural constituents. From a commercial point of view two groups of materials have been identified: the β - glass material exhibits high strength at room temperature, but at temperatures exceeding 1000°C its strength decreases rapidly due to the softening of the intergranular glass. The β -YAG material, however, has a lower room temperature strength, but retains its strength and creep resistance up to 1400°C.

Fabrication Techniques

The sialon ceramics can be fabricated through the usual ceramic processing techniques described earlier. The actual process depends upon the properties required and the application requirements in terms of size, shape, etc.

Applications

Sialon materials have already found a number of industrial applications, (e.g., cutting tools, welding applications, extrusion dies, seals and bearings, mining equipment and armour plating, molten metal handling, wear parts and refractories).

Commercial Production

In June 1983 Lucas announced that it had joined forces with the Cookson Ceramics Group to form a new jointly owned company called Lucas Cookson Syalon Ltd., Solihull, England. Lucas Cookson have been aggressively marketing their technology and have entered into licencing agreements with a number of companies, (e.g., Sandvik of Sweden, Kennametal and Carborundum in the USA, and NGK and Hitachi in Japan). Sandvik, Kennametal and NGK are using this technology for the manufacture of cutting tools.

3.3.3.3 Silicon Carbide (SiC)

General

Silicon carbide is an old material with a long history of industrial use. Its importance as an engineering ceramic material was recognized only recently - long after silicon nitride had gained prominence. To some extent, the initial problems with silicon nitride, particularly sintering problems, were responsible for catalyzing work on silicon carbide. Another important reason is the recognition that the diverse engineering requirements cannot be met with just one material such as silicon nitride, and that a spectrum of materials is required. An evaluation of the intrinsic properties relative to those of the few other covalent materials indicated that SiC had some advantages, particularly resistance to thermal shock. In addition, the superior elastic modulus and sublimation temperature of SiC were found to be desirable characteristics for high-temperature performance.

Silicon carbide exists in two crystalline forms. They are the α-form which has a hexagonal structure, and the β-form, which is cubic. The former has been known for a long time and is the crystal form of the products on the market to-date. The β-form is new and has received considerable attention because it can be sintered without pressure.

Production

Silicon carbide was first produced in 1881 by Colson and Schutzenberg, but the discovery is generally attributed to Acheson. He produced a small quantity of the material in 1891 by passing a strong electric current from a carbon electrode, through a mixture of clay and coke. Recognizing the abrasive properties of the material, Acheson founded the Carborundum Company, and in 1893 had installed a capacity of 7 tons/year, to be sold mainly to gem polishers as a substitute for diamond dust.

Most of the silicon carbide powder used today is produced by the Acheson process. High grade silica sand and carbon in the form of coke or antracite coal are reacted in an electric arc furnace. The overall reaction is:

$$SiO_2 + 3C \longrightarrow SiC + 2\,CO$$

The masses of SiC crystals from the furnace are broken up, further crushed and cleaned by acid or alkali treatment, then washed and dried. The crude SiC grain is further crushed, size-classified and magnetically treated to remove iron contamination from the crushing mills. The preparation of various mesh-size powders requires an elaborate process plant with grinding, screening and fine-particle separation/elutriation systems. The finest powder usually produced is about 10 microns or 1250 mesh. For engine applications, finer powders are required and are obtained by further milling the powder in silicon carbide mills. This additional step to reach micron and submicron size powders is likely to significantly increase the cost of the powder.

Recently, commercial production methods for the production of beta silicon carbide have been developed.

Commercial production of silicon carbide reached about 400,000 tons/year by 1960. In the early 1970s, the free world production peaked at about 475,000 tons/year, but declined to about 400,000 tons/year in 1981.

Silicon carbide production has long been established in North America and Europe, in areas that had a cheap source of electric power. Historically, hydroelectric power was the cheapest available source (the industry was established around Niagara Falls). In Europe, the industry was established in Norway, France, West Germany, Italy and Switzerland. Much of the industry remains centred in these areas, although production units have now been set up elsewhere, either in places where there is a large market (such as Japan) or where there is an alternative source of cheap power (such as the ESK plant in Illinois, USA).

In Canada, five companies operate six production facilities in the areas near the St. Lawrence River and Niagara Falls, Ontario: Canadian Carborundum Ltd., Electro Refractories & Abrasives Canada Ltd., the Exolon Company, the General Abrasive Company, and the Norton Company of Canada. Nearly all the crude SiC manufactured in Canada is shipped to the USA for crushing and processing.

The consumption of silicon carbide for industrial applications can be grouped as follows:

Application	Estimated Consumption (%)
Abrasives	40
Refractories	30
Metallurgical	25
Electrical, other	5

The above averages are for the free world markets. In Japan, however, the refractory applications consume about 75 percent of local production, followed by abrasives (15 percent), metallurgical and other applications (10 percent).

Fabrication of Silicon Carbide Components

All the ceramic fabrication and processing techniques described earlier are used in the manufacture of silicon carbide components. Sintering of SiC to achieve high density is influenced by impurities, particularly oxygen and elemental silicon. Hence, sintering aids such as boron and free carbon are added. As well, it is advantageous to start with β-silicon carbide powder, instead of α-silicon carbide, because the rate of growth of the former is much lower than that of the latter.

Four types of silicon carbide products which can be used for engineering applications are commercially made:

- Refel SiC
- KT SiC
- Noralide SiC
- CVD SiC

Refel SiC

Refel SiC is a self-bonded silicon carbide manufactured and marketed under licence by British Nuclear Fuels Ltd. (BNFL). Originally developed by UKAEA as cladding for nuclear fuel in high-temperature gas-cooled reactors, Refel-SiC has been manufactured and marketed since the early 1970s.

In this process, α silicon carbide and graphite powders are mixed with an appropriate binder, formed into the desired shape and then sintered. By adusting the ratio of SiC to graphite, the free silicon content is adjusted to the desired level. In all cases, a minimum of 8 percent of free silicon remains in a product which is fully dense and impermeable. Complex shapes can be fabricated by green-machining parts before siliconizing, or after siliconizing by diamond grinding. The process of siliconizing occurs in a partially evacuated chamber where silicon monoxide, evaporating from a silicon pool in which the body is placed, reacts with the outer body layer at a temperature of 1600-1700°C. The inner body acts as a wick through which silicon rises by capillary action; reacting exothermally with the free graphite forming β -silicon carbide and leaving an excess of silicon in a continuous matrix through the structure.

KT-SiC

This is a product of the Carborundum Company and is formed in a manner similar to the Refel process.

Noralide SiC

Noralide NC-400, a Norton Company product, is a relatively pure recrystallized silicon carbide (99 percent minimum purity) prepared by crushing and milling coarse SiC to provide a particular bimodal particle size distribution. In contrast to the siliconizing processes described above, the material is sintered in the temperature region 2100-2450°C; the exact temperature being dependent on the desired microstructure and service conditions in use.

CVD-SiC

Silicon carbide can be deposited on suitable substrates (at temperatures ranging from 1200 to 1700°C), from the decomposed products of methylchlorosilane and other similar compounds. By optimizing the process, dense stoichiometric coatings can be obtained.

3.3.3.4 Zirconia (ZrO_2)

General

Zircon ($ZrSiO_4$) and zirconia ceramics have been known and used for a long time. However, zirconia ceramics have become a very important engineering material in recent years. This came with the discovery in 1975, at the Australian Commonwealth Scientific & Industrial Research Organization, that zirconia ceramic's mechanical properties can be improved substantially by controlling its microstructure. In fact for some applications, particularly diesel engines, it is preferable to use silicon nitride and silicon carbide because of their lower thermal conductivity and thermal expansion coefficient, which is compatible with cast iron.

Production of ZrO_2 Powder

There are two important minerals from which zirconia is recovered commercially: baddeleyite, the oxide mineral form, and zircon, a silicate whose composition is $ZrSiO_4$. Zircon is the most common and widely distributed of the two. Important commercial deposits are mined in Australia, India, South Africa, and the USA. Most of it is used in manufacturing refractories, but it is also an important component for the manufacturing of zirconia and zirconium chemicals. World production of the mineral was 650,000 tons (430,000 tons of which were produced in Australia). The South African mineral, baddeleyite, which is less widely distributed, yields a material containing 96-98 percent ZrO_2 after processing. It is used largely in the manufacture of Al_2O_3-ZrO_2 abrasives and refractories. In Canada, a large deposit containing ZrO_2 has been found in Quebec, north of Schefferville, and is owned by the Iron Ore Company of Canada. It may find commercialization if the engineering application market for zirconia increases in the future.

Two types of processes are used in the production of ZrO_2 powders: chemical processes and a plasma process. Four types of chemical processes are used in the recovery of zirconia. First, in the chlorination and thermal decomposition process, zircon is directly chlorinated in the presence of carbon in the temperature range 800-1200°C to obtain $ZrCl_4$ (which is hydrolyzed with water to obtain zirconium oxychloride); calcination of the oxychloride yields ZrO_2 in granular form. Second, in the alkali decomposition process (which is the most common method for the manufacture of the pure oxide and chemicals), the minerals are reacted with sodium hydroxide to form sodium zirconate, which subsequently is converted into the oxide via zirconium sulfate. Third, in the lime fusion process, the mineral is reacted with dolomite in the 1100-1600°C range, and ZrO_2 can be obtained directly from the reaction products. Fourth, in the plasma process, the mineral in powder form is directly fed into the plasma arc for decomposition into ZrO_2, and is recovered by treatment with caustic soda.

"Stabilization" and "Toughening" of Zirconia

Pure zirconia, ZrO_2, is not a useful ceramic material because it undergoes crystallographic transformations accompanied by volume changes, which result in the cracking of the ceramic during thermal cycling. However, it can be useful as a 'stabilization' and 'transformation-toughening' technique. The former technique is several decades old, but the latter was discovered only in 1975.

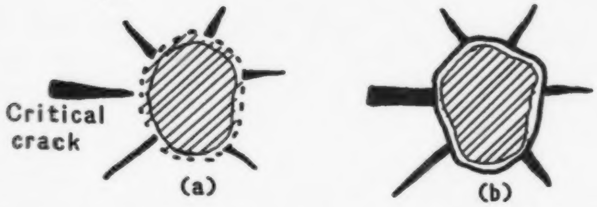
ZrO_2 exhibits three polymorphic modifications that are temperature-dependent: monoclinic, tetragonal and trigonal. The monoclinic form is stable at room temperatures of up to 1000°C, where it transforms into the tetragonal phase. This is stable up to about 1900°C, where it inverts to the trigonal form, in turn stable to the melting point of about 2700°C. Zerconia can be stabilized in a cubic form by incorporating suitable oxide additives. Of most recent interest is the toughening, resulting from controlled partial stabilization to produce partially stabilized zirconia, or PSZ.

The tetragonal-monoclinic transformation is of technical importance, in that it is associated with a large volume change (3 to 5 percent). This can cause cracking of the individual particles. The technology of stabilizing with CaO has been known for several decades, and the materials have been used for a number of applications (e.g., refractories). Improved products have been developed by stabilizing the structure with MgO and Y_2O_3 in recent years. As a result of commercial demands, powders corresponding to ranges within 0 to 20 weight percent of CaO, MgO and Y_2O_3 are now available (usually corresponding to compositions which give partially stabilized zirconia). For example, Magnesium Electron Company, the British subsidiary of Alcan, markets the following powders:

Stabilizing Oxide	Weight Percent
CaO	4, 5.5, 8, 10
MgO	4, 5.0, 8, 21
Y_2O_3	4, 6.0, 8, 16

Zirconia-toughened ceramics (also called ZTC), owe their beginnings to the 1975 discovery that the strength and toughness of zirconia can be increased substantially by utilizing the volume expansion and shear strain developed in the tetragonal-monoclinic (t-m) transformation to control the microstructure, and hence the properties. It is generally recognized that the t-m transformation of ZrO_2 particles occurs in a ceramic matrix (cubic ZrO_2 or another ceramic such as Al_2O_3).

on cooling through the transformation temperature, a volume expansion of 3 to 5 percent occurs in the ZrO_2 particles, causing a crack to form as shown below:



The martensitic transformation that occurs in ZrO2 (tetragonal to monoclinic at 900-1100 C) with its 3-5% volume expansion, develops microcracks around the ZrO2 particles, (a). A crack propagating into the particle is deviated and becomes bifurcated (b), thus increasing the measured fracture resistance.

Tangential stresses are generated around the transformed particle which induce microcracks in the matrix. These microcracks, by their ability to extend in the stress field of a propagation crack or to deflect the propagating crack, can absorb or dissipate the energy of the crack, thereby increasing the "toughness" of the ceramic. The optimum conditions are met when the particles are large enough to transform, but small enough to cause limited microcrack development. To achieve maximum toughness, the volume fraction of ZrO_2 inclusions must be at an optimum level.

Stress-induced transformation "toughening" depends on the fact that the t-m transformation can be prevented either by controlling the size of the ZrO_2 inclusions below a critical level, or by providing a constraining pressure on it by the matrix (i.e., the ZrO_2 particles are retained metastably in the tetragonal form). These fine particles can be introduced as a second phase during the initial fabrication (e.g., zirconia in alumina, or developed as a second phase by heat treatment during or after sintering).

Microstructural design of zirconia toughened ceramics is a very active area of research now because of the potential for engine and other wear-resistant applications. Three groups of materials are being studied:

- Ceramics based on partially stabilized zirconia
- Dispersed zirconia-containing ceramics
- Complex zirconia systems

Fabrication of Ceramic Components

Monolithic zirconia (PSZ) ceramic components are made by standard ceramic processing techniques.

For many engineering applications (turbine blades, diesel engine components, wear-resistant applications), coatings are used. The coatings are applied by plasma techniques. Equipment, materials and technology are marked by a number of companies, (e.g., Metco which has manufacturing/distribution facilities in the U.S.A., Canada, Europe and Japan).

3.3.4 Advanced Functional Ceramics

3.3.4.1 General

The advanced 'functional' ceramic category comprises advanced ceramics where there are electrical, electronic, magnetic, optical, chemical, biological and nuclear functional properties used. From an application point of view, they are usually grouped as follows:

- Electronic Ceramics
- Chemical & Biological Ceramics
- Nuclear Ceramics

3.3.4.2 Electronic Ceramics

The application of electronic ceramics depends upon their electromagnetic properties (i.e., their properties are dependent upon the interactions of electrons [or ions] in their structure). Components are classified by their electromagnetic properties into the following categories:

- Insulating Ceramics
- Dielectric Ceramics
- Piezoelectric Ceramics
- Pyroelectric Ceramics
- Magnetic Ceramics
- Optoelectronic Ceramics
- Semiconductors
- Ionic Conductors

Insulating ceramics are non-conductors. Typically, they are made of alumina, Al_2O_3, and are widely used as substrates for electronic circuitry (including ICs and LSIs) because of their excellent characteristics. These include: smooth, uniform surfaces; ease of processing; excellent mechanical strength; high chemical stability; high non-conductivity in high frequency; and relatively high thermal conductivity which enables rapid heat transfer. However, with miniaturization of electronic circuits, the need for materials with higher thermal conductivity has increased. Several competitive materials are being developed: aluminum nitride (AlN), beryllium oxide (BeO) and silicon carbide (SiC) are just a few. Their properties are compared in Table 2.

Table 2

Properties of Ceramic Substrate Materials
(After Toshiba)

Quantity	Units	Materials			
		AlN	Al_2O_3	BeO	SiC
Thermal conductivity	W/mk	100	20	250	270
Resistivity	10^{14}ohm cm	-1	-1	-1	-1
Breakdown voltage	kV/cm	140	100	100	0.7
Dielectric constant	none	8.8	8.5	6.5	40
Tan delta	10^4	5-10	3	5	500
Thermal expansion	10^{-6}/C	4.5	7.3	8	3.7
Density	g/cm^3	2.8	3.7	3.2	4.8
Strength	kg/mm^2	45	23	20	45

Dielectric ceramics have been known for a long time, and because of their ability to store electricity temporarily by dielectric polarization they are excellent materials for capacitors, one of the most important of all electronic components. For example, stereo units incorporate more than 50 capacitors, and TV sets and video tape recorders each contain between 100 and 200 capacitors. Barium titanate, $BaTiO_3$, for improved and better dielectric ceramic materials, exists to meet sophisticated needs as a result of the development of chip technology (particularly for high-frequency applications). Active research is in place on materials based on other ferroelectrics, such as sodium niobate, $NaNbO_3$. Murata Erie Canada is the only manufacturer in Canada.

Piezolectric ceramics are special ceramic materials which have the ability to interconvert electrical and mechanical energy into one another, (e.g., electrical energy can be converted into mechanical and vice versa). They play a very important role in a number of applications such as filters, clock resonators for microcomputers, buzzers, ultrasonic sensors, blood pressure sensors and communication sensors. They are particularly important for undersea applications - civilian as well as military. The material that is extensively used at present is a lead zirconate-lead titanate based material, usually known as PZT. The demand for new and better piezoelectric materials has increased considerably because of defence needs, particularly in the USA. Considerable commercial activity exists in Canada in this area: Almax Industries, Lakeside Electronics and BM Hi-Tech are companies active in their manufacture and in R & D.

Pyroelectric ceramics are a special group of piezoelectric materials. They react to the slightest differences in temperature. For example, they are very sensitive to infrared radiation and are used for fire alarms, burglar alarms, infrared detectors, etc.

Magnetic ceramics, also known as ferrites, have been known and in use for several decades. Two types of ferrites are used: hard ferrites, which are permanent magnetic materials (based on barium hexaferrite, $BaO.6Fe_2O_3$), are used extensively in loudspeakers and other applications; and soft ferrites (based on $MnZnFeO_4$), act as magnetic materials in the presence of an electric field and are used in a wide range of applications such as TV sets, antennas and magnetic tapes. In Canada, Neosid is the only manufacturer. Northern Pigment manufactures and markets iron oxides for the manufacture of ferrites.

There are three important applications for optoelectronic ceramics: optical fibres, optical windows and optical filters. The most important application for optical fibres is in fibre optic communications systems, including commercial telecommunications, military communications, and computer-to-computer data communication links. Other potential end uses include optical sensing, optical signal processing and optical computing. A new technology called "integrated optic circuits" is being developed both in the USA, Japan and Europe, and is expected to offer significant performance and cost-savings benefits in fibre optic systems. However, a number of technical barriers exist and will have to be overcome before such devices achieve commercial acceptance and diffusion. In Canada, Canstar Communications of Winnipeg (a subsiduary of Canada Wire Cable Co. Ltd.) is manufacturing fibre optics cables which will be used in trans-Canada communications links being established by CN Rail and CNCP. Bell Northern and Northern Telecom Canada are also active in related areas.

Semiconducting ceramics are used for a number of applications, such as PTC thermistors that control temperature (posistor), heating elements, safety devices for electronic devices (varistors) and other applications. This is a very active area because of the need in high-technology industries. Considerable activity exists in Canada on semiconductors in industry, university and government laboratories.

Ionic conductors are comparatively new materials and are variously known as solid-state electrolytes or superionics. These materials have the attractive property of selectively conducting either cations or anions while remaining electronic insulators. As a result, the nearly 40 known materials, have potential for a wide variety of applications: high-temperature furnace elements, high-temperature specific-ion sensors, high energy-density batteries, fuel cells, electrolysers, thermoelectric generators, specific-ion pumps, timers and coulometers, pressure and temperature transducers and electrochromic displays, to list a few. Canada has a long history of research and development activity in this area, beginning in 1975. The Ceramic Group at CANMET, EMR, and groups at McMaster and Queen's universities have been active for a number of years. Recently, Almax Industries and Magna International have shown commercial interest, the latter for sodium-sulfur high density batteries for electric vehicle applications.

3.3.4.3 Chemical & Biological Ceramics

Ceramics have been used for chemical corrosion-resistant and catalytic applications for decades. Refractories and chemical porcelain, as well as chemically resistant glasses are well known. Alumina-and aluminosilicate-based catalysts have been used in the petrochemical industry. With improvements in the properties of ceramic materials using advanced ceramic process technologies and the inherent good properties of ceramics, new applications are being developed and the future looks very promising.

Application of ceramics for biological applications is comparatively new. With the present emphasis on biotechnology, the industrial scope for advanced ceramics appears to be good for special catalyst supports, reaction vessels, etc. Use of advanced ceramic implants and zirconia based teeth are being developed in Japan and are expected to have significant commercial potential in the future.

3.3.4.4 Nuclear Ceramics

For nuclear applications, the ceramics, as well as possessing good strength, must possess good chemical resistance and radiation resistance properties. The former properties are required in the processing of fuel, as well as the handling of nuclear wastes which are corrosive. The latter properties are required in the hardware portion of the system.

Different types of advanced ceramics have been developed to meet the special needs of the nuclear industry. In fact, reaction-bonded silicon nitride was developed at Harwell for these purposes. Both silicon nitride and silicon carbide products are used. Also, special types of insulating materials are required for the hot-sections.

The ceramic material requirements for the 'fusion' reactors have to meet more stringent properties. It appears as though R & D in this area will increase substantially, because of the possibility of using nuclear generators in the US "Star Wars" program.

4. INDUSTRIAL APPLICATIONS

4.1 General

From the data discussed in Section 3, it is evident that advanced ceramics, as a class, exhibit superior properties which make them useful in a wide range of applications. Some of these applications are relatively old (e.g., electronics and cutting tools). Nevertheless, the availability of better materials has made it possible for the development of new products which are technologically superior and/or provide significant economic benefits. The newer applications can be grouped into two categories: first, those applications where the currently available material technology can be used with advantage to yield benefits (e.g., energy, space and industrial products); second, the potential future applications requiring material technology which is still being developed. In general, all of these applications can be grouped into six categories, as shown in Figure 13:

° Automobile and Other Engines
° Cutting Tools and Machinery Parts
° Electronics
° Industrial Products
° Energy and Space
° Consumer Products

4.2 Automobile and Other Applications

4.2.1 Advantages of Using Ceramics

The driving forces behind the current interest and feverish effort to develop and commercialize advanced ceramics for engine applications are: the need to improve energy efficiency; the need to achieve multifuel capability without deleterious environmental problems; the need to overcome material cost and supply problems; and most important, to gain significant economic benefits. In the beginning, the motivating force for the use of advanced ceramics was the need of the military, but at present the driving force is economically based.

Currently, materials based on silicon nitride (Si_3N_4), silicon carbide (SiC), and zirconia are being developed for engine applications. Silicon nitride and silicon carbide in particular are attractive because of their high strength at high temperature, good thermal shock resistance and excellent corrosion and erosion resistance. Zirconia is attractive because it has thermal expansion matching metals used in engines, low thermal conductivity, toughness and good oxidation resistance. This combination of properties is desirable, as it permits increases in the operating temperature of engines, which in turn result in improved fuel efficiency. Some typical examples of the potential energy gains to be achieved for various generic classes of engines are given in Table 3.

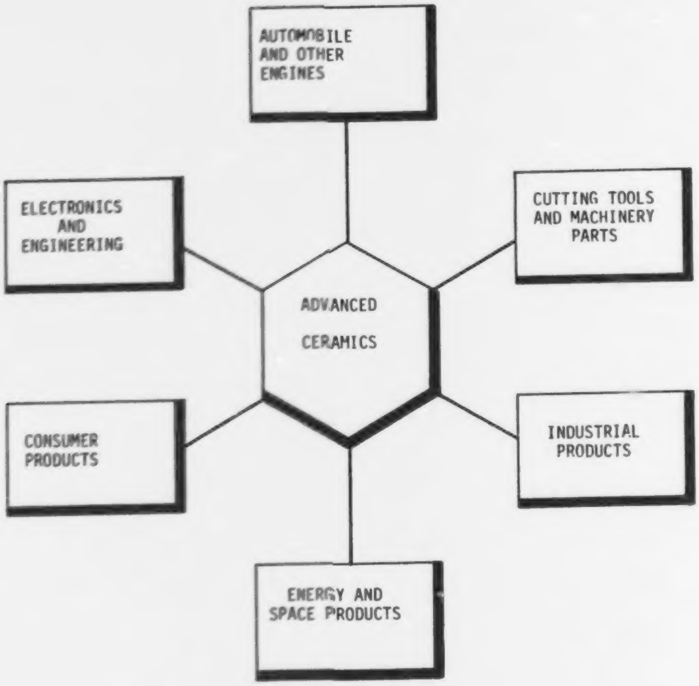

AUTOMOBILE AND OTHER ENGINES
ELECTRONICS AND ENGINEERING
CUTTING TOOLS AND MACHINERY PARTS
ADVANCED CERAMICS
CONSUMER PRODUCTS
INDUSTRIAL PRODUCTS
ENERGY AND SPACE PRODUCTS

FIGURE 13: Industrial Applications of Advanced Ceramics

TABLE 3

Ceramic Technology Payoff of Some Typical Engines

Engine Type	H.P.	Range Configuration	SFC*	Power
Automotive GT	200	Regenerated, single-shaft 1350°C, TIT**	-27%	0
Truck FT	350	Regenerated, 2-shaft 1250°C, TIT	-27%	+30%
Light Ship GT	1000	Simple Cycle, 3-stage, 1350°C, TIT	-10%	+40%
Diesel	500	Adiabatic turbo compound Tmax 1050°C	-22%	+37%

* SFC - specific fuel consumption - (gm/W-hr), based on current state-of-the-art

** TIT - turbine inlet temperature

Ceramic components weigh less than metal components because of their lower density - up to 40 percent. The consequent lower weight and inertia translates into improved engine performance.

Another significant advantage is cost. Compared with superalloys used at present, the cost of ceramic components is expected to be significantly low when the research and development work is complete and commercial manufacturing and mass production techniques are in place. Furthermore, from a national security point of view, ceramics have the advantage of not being critical materials, because the raw materials are readily available.

The over-all advantages of using advanced ceramics in engines is shown schematically in Figure 14.

4.2.2 Current Status of Development of Engines

The different types of engines under development using ceramic components are identified below:

(i) Gas Turbine Engines
(ii) Diesel Engines
(iii) Gasoline Engines

(i) Gas Turbine Engines

Gas turbine engines for three important applications are being developed:

° Aircraft Engines
° Automotive Engines
° Stationary Engines for Power Generation

Aircraft Engines

Gas turbine engines were originally developed for use in aircraft, (particularly for military applications). At present however, they power both military and civilian aircraft.

The operating efficiency of a gas turbine engine is compatible with the increase in the turbine inlet temperature. From its inception, development efforts have been in progress towards achieving this aim - the limiting factor being the availability of suitable high-temperature materials. Although noteworthy progress has been made by using better alloys, culminating in the present day superalloys, there is still room for significant improvements - both in terms of higher operating temperatures to achieve still higher energy efficiency and in reduced cost. The advantages to be gained by using silicon nitride and silicon carbide materials are clearly demonstrated by the data presented in Figure 15.

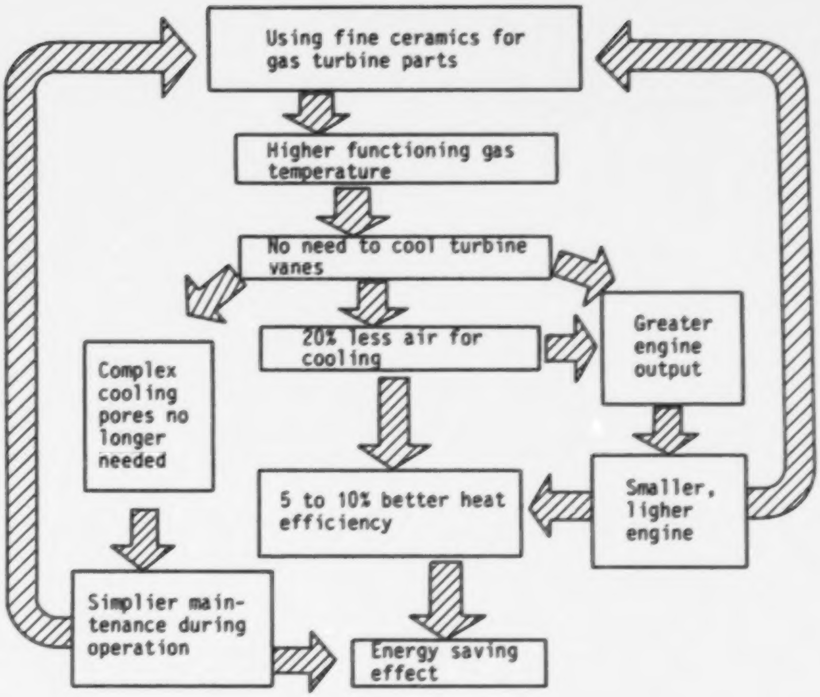

Using fine ceramics for gas turbine parts
Higher functioning gas temperature
No need to cool turbine vanes
20% less air for cooling
Greater engine output
Complex cooling pores no longer needed
5 to 10% better heat efficiency
Smaller, ligher engine
Simplier maintenance during operation
Energy saving effect

FIGURE 14: Benefits Resulting from Using Advanced Ceramics in Engines (Source: The Long-Term Credit Bank of Japan, Ltd.)

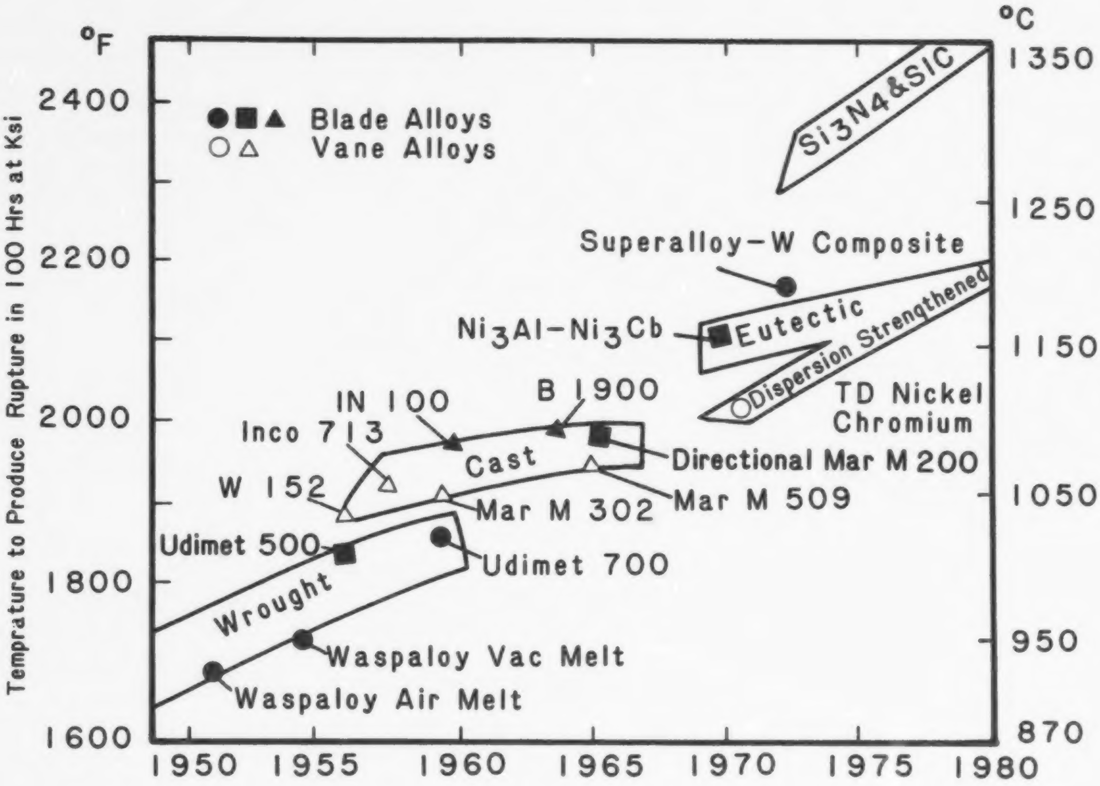


FIGURE 15: Trends in Material Capability for Gas Turbine Engines (Source: Reference 2, Bibliography page 164)

Because of safety and reliability requirements, the use of monolithic ceramic components in aircraft engines is still in the research and development stage. However, it was recognized quite early that ceramic coatings could insulate engine parts from hot combustion gases and were used for reducing metal temperatures of, and providing corrosion protection for, turbine blades. At present, the use of plasma-sprayed advanced ceramic coatings is in commercial practice.

A considerable amount of R & D work in this area is being done by almost all aero-engine manufacturers such as United Technologies (Pratt & Whitney), General Electric Company, Garrett Corporation and Rolls Royce.

Automotive Engines

An automotive gas turbine engine is similar to but not identical with the gas turbine engine used for aircraft propulsion. It generates power by driving a rotating turbine, using compressed high-temperature gas. Automotive gas turbine engines have many potential advantages, the most significant being the greater fuel efficiency compared with reciprocating engines - gasoline as well as diesel. Other advantages are lower noise and emissions, alternate fuel capability, lower oil consumption, cold weather starting capability and lower life-cycle costs. Gas turbine engines in aircraft have demonstrated lower maintenance requirements and longer life compared with piston engines.

In the last decade, significant progress has been made in the development of automotive gas turbine engines using advanced ceramics components. Silicon nitride and silicon carbide have been the preferred materials for engine parts; aluminosilicates for regenerators. The leading countries in developing this technology are the USA, West Germany and Sweden.

The United States was the first country to initiate full-scale research programs on the design and development of automotive gas turbine engines incorporating ceramic components. To date, two demonstration programs have been successfully completed and two new programs are in progress. The FORD/DARPA program demonstrated the technical feasibility of incorporating ceramic components - both stationary and rotating - in gas turbine engines. The GM/DOE program resulted in the successful demonstration of a gas turbine engine in a highway vehicle (on a routine basis with realistic operating conditions). The success of these two programs favoured the start of another program in 1980 - the Advanced Gas Turbine (AGT) program. Again this is a demonstration program fully funded by DOE. Two parallel contracts have been issued - one to the Detroit Diesel Allison Division of GM for the AGT-100 program (whose aim is to develop a two-shaft gas turbine engine and demonstrate its operational efficiency in a 1985 Pontiac Phoenix X-car), and the other to the

GARRETT/FORD team for the AGT 101 program (whose objective is to develop a single-shaft engine suitable for the FORD family of vehicles). The programs are still in progress and are scheduled for completion in 1990.

To date, West Germany has also made significant progress in developing gas turbine engines for cars and other vehicles. As part of a national effort initiated in 1974, three engine and seven ceramic manufacturers have contributed to the development. The three engine manufacturers were Volkswagen, Daimler Benz and MTU. The development program of the ceramic manufacturers is summarized in Table 4.

Volkswagen has done extensive R & D on the performance evaluation of ceramic components under simulated test conditions. However, Daimler Benz have built a demonstration engine with silicon nitride components and incorporated it into a vehicle which has performed well in road tests. The company is continuing the development with the hope of commercializing in the future.

In Sweden, both Volvo and SAAB are actively involved in the development of gas turbine engines, with support from a number of ceramic companies, particularly ASEA. Volvo has been developing jointly with United Turbine Company KTT: Mark-1 and Mark-2 engines for vehicular applications. These engines are based on a three-shaft design, combining engine and transmission functions. Currently, the development of components and testing of engines is still in progress.

At present, Japan does not appear to be concentrating on the development of gas turbine engines for vehicular applications because of material and technological problems.

Stationary Engines for Power Generation

Only the USA and Japan appear to be active in this area. In the USA pioneering work was done by Westinghouse in the early 1970s with financial support from DARPA. Ceramic components were tested and appeared to be promising. However, because of reliability and cost problems, the project was discontinued. Several other specialized studies for the military have been done, but details are not available.

In Japan, considerable effort is being spent on the development of gas turbine engines for electric power generation. Design, development and testing is being carried out by the Advanced Gas Turbines for Engineering Research Association (AGTERA). This organization is a conglomeration of private industry and government laboratories. Mitsubishi is doing the high-pressure turbine development work. Hitachi is in charge of low- and intermediate-pressure turbines.

TABLE 4

Scope of Programs of West German Ceramic Manufacturers in the National Program

Company	Material	Forming Technology	Component
Anawerk	RBSN HPSN SiSiC SSiC	Slip Casting Injection Molding Hot Pressing	Stator Inlet Cone Rotor Hubs
Degussa	RBSN	Injection Molding	Blade Rings Single Blades
ESK	HPSiC	Hot Pressing	Blades, Hubs Rotor
Feldmuhle	RBSN	Injection Molding	Blades, Rings
Rosenthal	RBSN SiSiC	Foils Lamination Injection Moldoing	Recuperator Blades Segment
Sigri	SiSiC	Injection Molding Slip Casting	Combustor Inlet-Scroll
H.C. Starck	SiC Si_3N_4	Powder	

turbines. Toshiba is in charge of control equipment, and Kawasaki is doing the ceramic combustor work. Ishkawajima is responsible for power conditioning and transmission equipment. The pilot plant, located in Sodegaura City, is a 100 MW electrical power plant.

(ii) Diesel Engines

Although the diesel engine is relatively efficient, it still rejects most of its energy in the form of waste heat in the exhaust and cooling systems. Better utilization of waste heat in a simple, efficient and useable manner is the key to a more energy-efficient diesel engine. Use of advanced ceramic materials offers design options which were not available before, particularly eliminating cooling systems. Energy balance comparison for basic, turbocharged and turbocompound, and adiabatic diesel engines is shown thereafter. The significant improvements in energy efficiencies are very clearly presented, increasing from 35.6 percent to 48 percent as shown in Figure 16.

Development of advanced diesel engines containing ceramic components and coatings made of advanced ceramics - particularly silicon nitride and zirconia - is in progress in the USA, Japan, West Germany, the UK and France.

In the USA, Cummins Engine Company has been developing adiabatic turbocompound diesel engines with financial support from the US Army. Significant achievements have been made since the inception of the program in 1976. The technical feasibility was demonstrated in 1980 - a first-generation engine installed in a five-ton US Army truck has performed satisfactorily - and road tests have indicated a 30-50 percent increase in fuel efficiency. Work is in progress to further develop the technology. Several other industrial companies are also actively involved because of the potential market advantages: International Harvester Co.; Caterpillar Tractor Co.; Hauge International Co.; John Deere Co.; and Terratek Inc.

By far the largest industrial activity in the development of diesel engines exists in Japan. This is evident from Table 5 which lists the companies that are actively involved, as well as the type of R & D work that is being carried out.

(iii) Gasoline Engines

A large number of ceramic components are already in use in gasoline engine cars, as shown in Table 6. With increase in the use of computers to control engine efficiency and emissions, the number of ceramic sensors used is expected to increase significantly in the coming years.

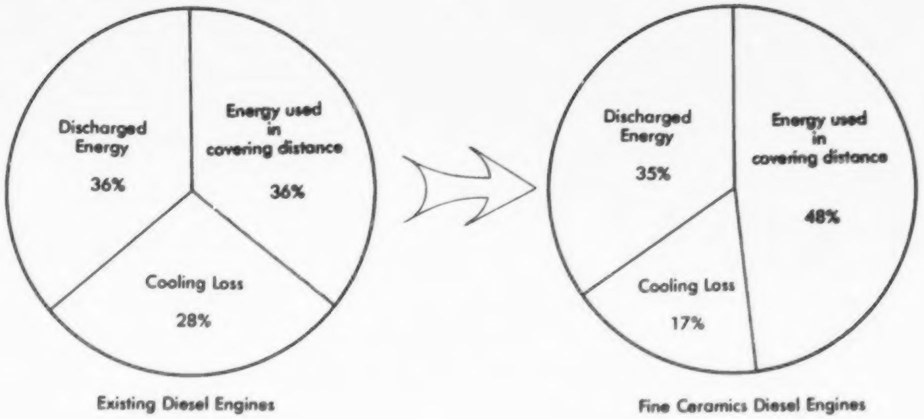


FIGURE 16: Energy Efficiency Improvement in Diesel Engines with Advanced Ceramics

TABLE 5

Research Trends of Japanese Companies in the Development of Ceramic Engine Parts

Type of part / Example of a company		Gas turbine engines	Engine combustion chamber exhaust type (diesel)						Engine moving-valve type								Others		
			Cylinder heads	Piston pins	Piston crowns	Cylinder liners	Hot plugs	Others	Rocker arm seats (valve side)	Rocker arm seats (push rod side)	Valve guides	Valve seats	Exhaust valves	Tappets	Cams	Others	Glow plugs	Piston ring anti-wear rings	Others
Auto and auto parts manufacturers	Toyota	△	△	△	△	△	△		△	△		△	△	△	△	△	△	○	△
	Nissan	△	△	△	△	△	△	△	△	△		△	△	△	△	△	△		△
	Mazda		△	△	△	△	△		△	△	△	△	△	△	△	△	△		△
	Honda																		
	Mitsubishi Motor	△			△	△	△	△	△	△	△		△		△		△		
	Suzuki						△						△						
	Fuji Heavy Industries								△	△	△			△	△	△			
	Daihatsu			△	△	△	△	△									△		
	Isuzu		△		△	△	○	△					△			△	○		△
	Hino		△		△	△		△	△	△			△	△	△	△	△		
	Nihon Piston Ring		△	△	△	△													△
	Nippon Denso			△	△														
	Izumi Motors				△														
Ceramics manufacturers, etc.	Kyocera	△	△	△	△	△	○	△	△	△	△	△	△	△	△	△	○		△
	NGK Insulators	△	△	△	△	△		△	△	△	△	△	△	△	△	△			
	NGK Spark Plug	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△			△
	Toshiba Ceramics	△		△	△	△		△	△	△	△	△	△		△	△			
	Hitachi Ltd.		△	△	△	△													
	Komatsu		△		△	△		△	△	△			△			△			
	Toshiba	△																	

Source: Information in newspapers, etc.

Note: △ = under research and development, ○ = already commercialized

(Source: The Long-Term Credit Bank of Japan, Ltd.)

TABLE 6

Ceramic Components Used in Automobiles

Component	Material
Functional Ceramics	
Oxygen sensor	ZrO_2
Knock sensor	PZT
Backup sensor	PZT
Electric buzzer	PZT
Thermo sensor for Water	$Fe_3O_4 \cdot CoMn_2O_3 \cdot NiO$
Thermo sensor for Exhaust	$Al_2O_3 \cdot Cr_2O_3$
Blower resistor	$BaTiO_3$
Fuel level switch	$Al_2O_3 \cdot Cr_2O_3$
Heater for intake gas	$BaTiO_3$
Condenser	$BaTiO_3$
Motor core	$Fe_2O_3 \cdot Mn_2O_3$
Insulator for spark plug	Al_2O_3
Substrate for hybrid IC	Al_2O_3
Substrate for choke heater	Al_2O_3
LED	GaP
EL	ZnS
Structural Ceramics	
Mechanical seal for water pump	Al_2O_3
Catalyst pelleted support	Al_2O_3
Catalyst monolithic support	$MgO \cdot Al_2O_3 \cdot SiO_2$
Fiber for FRM piston	$Al_2O_3 \cdot SiO_2$
Heat insulator for catalyst	$Al_2O_3 \cdot SiO_2$
*Glow plug for diesel engine	Si_3N_4
*Precombustion chamber for diesel	Si_3N_4
*Rocker arm tip	Si_3N_4
*Turbochargers	

(Source: US National Academy of Sciences)

All the components except the last four are now used in Toyota cars. Glow plug and precombustion chamber are used by Isuzu. NGK is supplying rocker arm tips for use in taxis. Turbochargers are being developed and both Kyocera and NGK are in the prototype production stage of about 1000 a month.

In addition to sensors, two other areas where advanced ceramic components are expected to find use as structural components are as wear parts and turbochargers.

Ceramic turbochargers are prime candidates for introduction to improve engine performance. Work is in progress to develop turbochargers in the USA, Japan and West Germany. In the USA, Ford Motor Company is actively developing silicon nitride based turbochargers. Although the company is said to have the necessary manufacturing technology, a business decision has not yet been made. Carborundum Company is developing silicon carbide based turbochargers for Volkswagen of Germany and other possible users. In West Germany, Volkswagen has a very active program for the development and commercialization of turbochargers for both diesel and gasoline cars. They are evaluating components made by a number of domestic (SIGRI-SiC,ESK-Si_3N_4) and foreign manufacturers (Carborundum-SiC, NGK-Si_3N_4).

4.2.3. Outlook

4.2.3.1 Technological Issues

In spite of the tremendous effort and resources committed to the development of advanced structural ceramics for engines over the last 15 years, and the significant technical achievements to date, a number of major technological barriers exist. The future success, in terms of commercial acceptance and market penetration, depends upon finding timely solutions to these problems.

From the material development point of view there are three important barriers. First, **reproducibility in manufacturing.** Due to the inherent brittle nature of ceramic materials even the smallest flaws introduced during the material processing and component fabrication steps will have serious, deleterious effects on performance. Work is in progress to develop the necessary technology to produce defect-free components through a better scientific understanding of the properties of the starting powders, better techniques and, more important, through a better understanding and control of the microstructure of the components which, in turn, controls the properties and performance of the components.

Second, **manufacturing cost** is too high. The total manufacturing cost comprises cost of powder, material processing and fabrication cost, finishing cost and, finally, inspection and testing cost. At present, all these costs are high - some more so than others. A representative breakdown of these costs is given below:

Manufacturing Step	Relative Cost
Powder	1
Process	2-3
Finish	7-10
Testing	1-2

There is a consensus amongst the technical community that material processing and fabrication costs can be controlled by the selection and optimization of currently available technology, particularly when mass production techniques are in place. The cost of the powder is also expected to decrease, however, because it is controlled essentially by the total demand for all applications - engine as well as others. Since the engine market for these powders is projected to be roughly half of the total commercial acceptance, market penetration of ceramic components in engines will largely influence the final price. The cost of finishing the components is very high because of the necessity to diamond polish them. This appears to be the single most important parameter influencing the final manufacturing cost. The answer lies in using near-net-shape processing techniques and controlling the process parameters. Although this appears to be possible for simple shapes, the complex shapes in the engines will remain a problem. In spite of intense effort by the ceramics manufacturers, the problem still remains a technical challenge, and the final outcome is far from certain. Since the ceramic components for engine applications should theoretically have no defects, it is clear that proper testing and evaluation techniques are needed. To date there are no satisfactory methods, with the exception of 100 percent inspection. For some complex parts, there are no techniques at all, except destructive testing.

To be used in automobiles, ceramic engines must be mass-producible at low cost. The overall manufacturing cost for ceramics is estimated in Japan to be about 20,000 to 30,000 yen/kg (US$ 80-120/kg). It is widely believed that ceramics cannot be used economically in engines until the cost of the finished component is below 5,000 yen/kg (US$ 20/kg). The present costs of ordinary and high purity silicon nitride (Si_3N_4) are 6000 yen/kg and 22,000 yen/kg respectively. For engine applications it is necessary to use the high-grade materials making the present-day cost of the component about 220,000 yen/kg (US$ 880/kg) - assuming the manufacturing cost to be 10 times the raw material cost. From the foregoing outline, it is clear that a significant gap exists between the present-day cost and the market-driven cost. Silicon carbide, SiC, is much cheaper. (The alpha-variety and the beta-variety cost 3000 yen/kg and 8000 yen/kg. respectively. Although it has a better cost profile, its properties are not entirely satisfactory. It is likely that both of them will be used, with the cost determining the mix.

Third, **reliability in service** is a barrier. Reliability problems refer to unacceptably high probabilities of failure in service. It is now well recognized that reliability is the single most important barrier, next to cost, for the commercialization of new ceramic engine systems. User acceptance and market diffusion of new engine systems depends on achieving reliability levels approaching those of conventional engine systems. To date, all the available data on reliability - with the exception of a few vehicle demonstration runs - are based on prototype testing on test beds. It is apparent therefore, that the timeframe for engine acceptability will be long.

There are a number of other issues that border on technology that will influence the commercial acceptance and market penetration of ceramic components in engines. Although they are not as important as cost and reliability problems, these are still important issues:

- Because of investment cost and timing problems, it is very likely that the present metal engine design will not change, at least for some time. Therefore, ceramic components will have to be used with metals. Two problems that have to be addressed are lack of understanding of the brittle properties of ceramics by the design engineers who are trained to deal with metals, and production problems - again related to the unfamiliarity with ceramics.
- Problems associated with maintenance servicing during the early years.
- Public acceptance. That ceramics are brittle and break on impact is common knowledge. Therefore, public awareness will be required, at least during the early years.

4.2.3.2 Automobile Industry Response

The motivating force for considering the use of ceramic components for automobile engine applications were gains in energy efficiency resulting in fuel savings, reduction in toxic emissions from exhaust gases to meet environmental safety requirements, and the potential for reduction and/or elimination of the need for critical imported raw materials. All these forces existed in the 1970s and still do. However, the business environment for the automobile industry has undergone dramatic changes, and the needs and priorities have changed significantly. This is particularly true in the USA and in Japan.

In the USA the auto industry has restructured itself after the recession of 1982, not only to protect the domestic market, but also to improve its international competitive position (particularly with respect to Japan). Reduction of unit cost and improved performance are the primary goals. This is being accomplished by a number of steps: just-on-time delivery of parts to reduce inventory costs; improved productivity during manufacturing by using robots; and component and system design improvements. Both the energy efficiency and toxic emission requirements have been met - the former by the downsizing of cars (substituting materials to reduce weight and incorporating aerodynamic body designs; and the latter by using catalysts and sensor technology to improve combustion performance. Furthermore, the relative importance of improving energy efficiency of engines is secondary to other considerations because of the present world oil pricing situation and the fact that the energy shortage predictions have not come true.

Both the largest US automobile manufacturers - Ford and GM - are actively involved in the development of advanced ceramic engines. Therefore, they have first-hand experience in the status of technology development; technological and cost problems and the projected timeframe for solutions to these problems; and more important, the cost of changing over from the present generation of metallic engines to ceramics-based engines. According to some industry sources, the three important considerations that impinge on the final outcome are:

- ° Engine design is usually decided at least five years before production is initiated, because of the required lead time.
- ° Engine design (family) must be useful for at least a 20-year period to justify investment.
- ° To replace metals, other things being equal, the cost of the ceramic components must be much lower, and/or energy efficiency must be at least 10 percent higher.

Neither Ford nor GM appears to be committed to commercialization at the present time, indicating that the time frame for the introduction of ceramic engines is far in the future.

A recent study by the US Commerce Department projects the following timeframe for commercial introduction of advanced ceramic components in engines:

End Use	1985	1990	1995	2000 ......
Selected Engine Parts	--------	--------		
Small Stationary Engines		----------	------	
Vehicular Engines		---	----------	------
Large Stationary Engines			----------	--------
Aircraft Engines				-----------

Charles River Associates presents the following scenario linking key milestones in the development of ceramic components for engine applications:

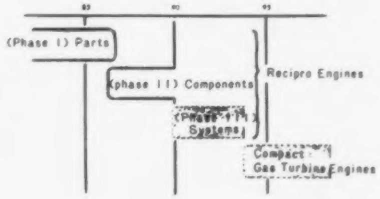
Milestone	Estimated Date of Commercial Introduction
Turbocharger Rotor	Middle 1980s
Uncooled Diesel	Late 1980s to Early 1990s
Adiabatic Diesel	Early to Middle 1990s
Gas Turbine	21st Century

Of all the automobile industries in the world, the Japanese industry appears to be the most committed to introducing ceramic engines over the long term. Both the automobile companies and the ceramic component manufacturers have joint programs to commercialize the use of ceramic components in engines. Some examples of business tie-ups are given below:

Automobile Company	Ceramic Company
Isuzu Motors	Kyocera Corporation
Mitsubishi Motors	Asahi Glass
Toyota Motor Corp.	Toshiba Ceramics
Nissan Motors	Hitachi Chemicals
Komatsu	Toshiba Ceramics

To date, a number of companies have been introduced into commercial production. Silicon nitride glow plugs and swirl chambers for diesel engines are being manufactured at the rate of about 30,000 per month, and turbochargers are going into prototype production at the rate of about 1000 per month.

Notwithstanding this unique success, the industry and the technical community are aware of the serious problems to be solved - reproducibility in manufacture, reliability in service, and cost. Recent discussions indicate that the Japanese consider the development of the ceramic engine as the final goal, with limited but definite target applications which can be commercialized. The following development scenario for automobile ceramic components has been put forward by the Fine Ceramics Working Group of MITI.



(Source: MITI)

4.3 Cutting Tools and Machinery Parts

4.3.1 Background

Metal cutting tools have been used since ancient times to remove excess materials from products during the manufacturing process. Over time, numerous changes have taken place in the manufacture and use of cutting tools that have increased productivity at the material removal or finishing stage of production. The development of improved machine tools to hold and guide the cutting tool has added to the power, speed and precision with which material removal can be performed. With the introduction of numerically controlled machine tools and the need to improve productivity, a tremendous pressure is being exerted on the cutting tool manufacturers to develop better and more efficient products.

In general, the cost of the cutting tool itself is a very small part of the overall cost of the machine operation. The cost of metal-cutting depends on a variety of factors, the most critical of which are cutting speed, the life of the cutting tool, and the probability and cost of failure in use. These factors, in turn, depend upon the cutting tool material and its properties, the material properties of the parts being machined, the characteristics of the machine tool which holds and guides the cutting tool, and the nature of the cut itself.

4.3.2 Ceramic Cutting Tools

In the 1930s high-speed steels were replaced by cemented tungsten carbide (WC) tools, followed by titanium carbide (TiC), because in cutting, hard materials are used to cut softer materials, and because ceramics are inherently hard, cutting tools based on alumina (Al_2O_3) were developed in Germany during the Second World War. These were adopted commercially in North America in the mid 1950s.

The early history of ceramic cutting tools was characterized by a persistent failure to match the properties of ceramic tools with the job being done. It is now recognized that there cannot be one-to-one substitution of ceramic cutting tools for either cemented carbide or metal cutting tools; and that the properties of the ceramic, such as strength, microstructure, and shape, have to be tailored to suit the workpiece. Between 1960 and 1970, a better understanding of the foregoing factors resulted in better alumina-based cutting tools (additions of titanium, titanium carbide and tungsten carbide were made to improve the strength of alumina). Harder materials such as polycrystalline diamond (PCD) and cubic boron nitride (CBN) followed.

4.3.3 Advantages of Advanced Ceramics Cutting Tools

Although alumina-based cutting tools were useful, they were not entirely satisfactory because of their brittleness and low thermal conductivity. The development of silicon nitride based materials for engine applications and the recognition of their good properties such as hardness, toughness and good mechanical properties at high temperatures, provided an opportunity to use these materials for cutting tool applications. The cutting tip can operate at much higher temperatures, compared with alumina and other older materials. The relationship between increased cutting speed and the substitution of different materials since 1800 is given in Figure 17. Increased cutting speeds under proper conditions allow for less expensive operations and promote increased use of automation to improve productivity. Projected costs for different materials as a function of cutting speed are shown in Figure 18.

4.3.4 Industrial Activity

Cutting tools made of advanced ceramics are being manufactured and marketed by a number of companies in the United States, Japan, West Germany, Sweden and the UK.

Production of advanced ceramic cutting tools in the USA is in the hands of six companies: GTE Sylvania, GE Carboloy, Kennmetal, Greenleef, VR/Wesson, and Kyocera. Kyocera, the US subsidiary of Kyoto Ceramics of Japan, appears to be the largest tool manufacturer in the USA, with sales of about $1.5 million in 1983. It gained large-scale entry into the US market through the 1982 acquisition of the US subsidiary of Feldmuhle of West Germany. GTE Sylvania, after its acquisition of Valeron, is probably the next largest manufacturer, with combined sales of about $1 million in 1983. Greenleef, which recently acquired Nucermet Division of B & W, is also expected to have sales in the $1 million region. Kennmetal, which has a licencing agreement with Lucas Cookson of England for the sialon technology, is estimated to produce about $50,000 worth of products. Both GE Carboloy and VR/Wesson are small companies.

About half the advanced ceramic cutting tools sold in the USA in 1983 were manufactured principally or entirely in Japan. The leading exporter is NTK, a subsidiary of NGK Spark Plug Company. The products are finished in a plant in the USA. The total sales are estimated to be about $4-5 million per year, or about 40 to 50 percent of the total US market. Other major importers include Sumitomo and Nippon Products. A list of major companies that make or sell cutting tools in the USA is given in Table 7. The total market penetration is about 1.5 per cent.

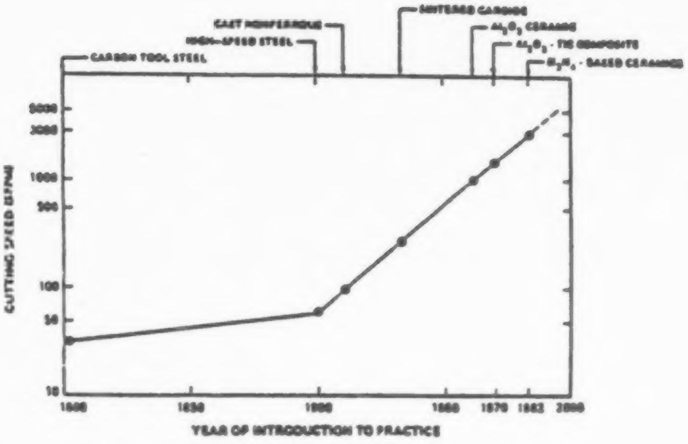


FIGURE 17: Cutting Tool Speed as a Function of the Year of Introduction of Material Into Practice

(Source: Charles River Associates)

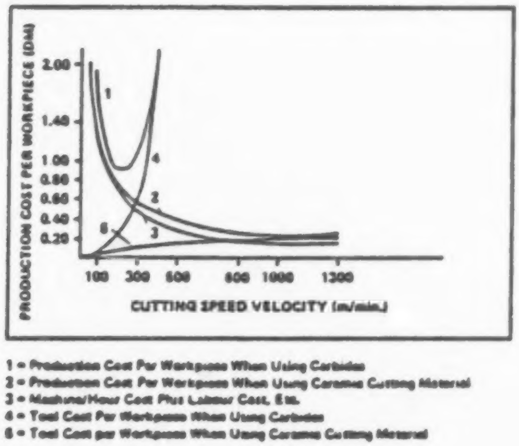


FIGURE 18: Production Cost Using Various Cutting-Tool Materials

(Source: Charles River Associates)

TABLE 7

Major Suppliers of Advanced Ceramic Cutting Tools to the US Market

Company	Composition	Process	Produced in United States	Produced Abroad
Nucermet	Al_2O_3 + TiC	Hot	x	
	Al_2O_3	Cold	x	
Greenleef	Al_2O_3	Cold	x	
	Al_2O_3 + TiC	Hot	x	
	Si_3N_4-based		x	
Kennametal	Si_3N_4-based	Cold	x	
	Al_2O_3	Cold		x
	Al_2O_3 + TiC	Hot		x
Kyocera	Al_2O_3 + TiC	Hot	x	
	Al_2O_3 + ZrO_2	Cold	x	
	Al_2O_3 + ZrO_2	Cold	x	
	Al_2O_3 + TiC	Hot		x
NTK*	Al_2O_3	Cold		x
	Al_2O_3 + TiN	Cold		x
	Al_2O_3 + TiC	Hot		x
Sumitomo	Al_2O_3	Cold		x
	Al_2O_3 + TiC	Hot (HIP)		x
Valeron	Al_2O_3	Cold	x	
	Al_2O_3 + TiC	Hot	x	
Iscar	Si_3N_4-based		x	

SOURCE: Charles River Associates; based on R.L. Hatschek, May 1981, "Take a New Look at Ceramics/Cermets". American Machinist: 165-172; and various industry contacts.

*These tools are believed to be pressed in Japan but ground in the United States.

Four principal manufacturers are largely responsible for Japanese ceramic cutting tool production: NGK Spark Plug Co., Sumitomo Electric, Diejet Kogyo, and Nippon Tungsten. Other suppliers include Mitsubishi Metals, Toshiba Tungaloy and Kyoto Ceramics. Advanced ceramic cutting tools have achieved greater market penetration in Japan compared with the USA, and form about 4 percent of the carbide-ceramics portion of the Japanese market.

The Europeans are considered to be the largest users of ceramic cutting tools. This is attributed to the fact that tungsten was difficult to obtain after the Second World War, causing them to adopt ceramic-cutting tool technology earlier and faster. Feldmuhle A.G. in Germany is the largest supplier of ceramic cutting tools for European use, with an estimated sales volume in 1982 of $12 million. Krupp-Widia is also expected to be in the ceramic cutting tool activity in the near future.

Sandvik of Sweden is very active in the ceramic cutting tool market. In addition to cemented carbide tools, they are manufacturing sialon-type cutting tools from the technology acquired from Lucas Cookson of the UK. No sales figures are available.

In Canada, the two principal manufacturers of cutting tools are Sandvik Canada Corporation of Mississauga, Ontario, and International Cutting Tools of Montreal. The former is wholly owned by Sandvik of Sweden, and manufactures carbide cutting tools for automotive (Windsor, Ontario), mining (Montreal, Quebec) and other applications.

4.4 Electronic Applications

4.4.1 Background

The use of ceramics in the manufacture of electronic components is based on their electrical, magnetic and optical properties. The electronic component business is relatively well established, with significant commercial production occurring since the 1950s.

From a functional point of view, eight different types of electronic ceramics can be identified. (See Figure 19). The relationship between type, property, composition and application is given in Table 8.

The nature of the electronic ceramics market is changing dramatically to accommodate developments and technological changes in the electronics industry. First, the old system of individual components, assembled into a system for particular applications, is being replaced with integrated systems where all the functional components are integrated (i.e., the integrated circuit). Second, miniaturization of electronic systems and equipment is taking place at a very rapid rate for a number of reasons, primarily to accommodate space constraints in

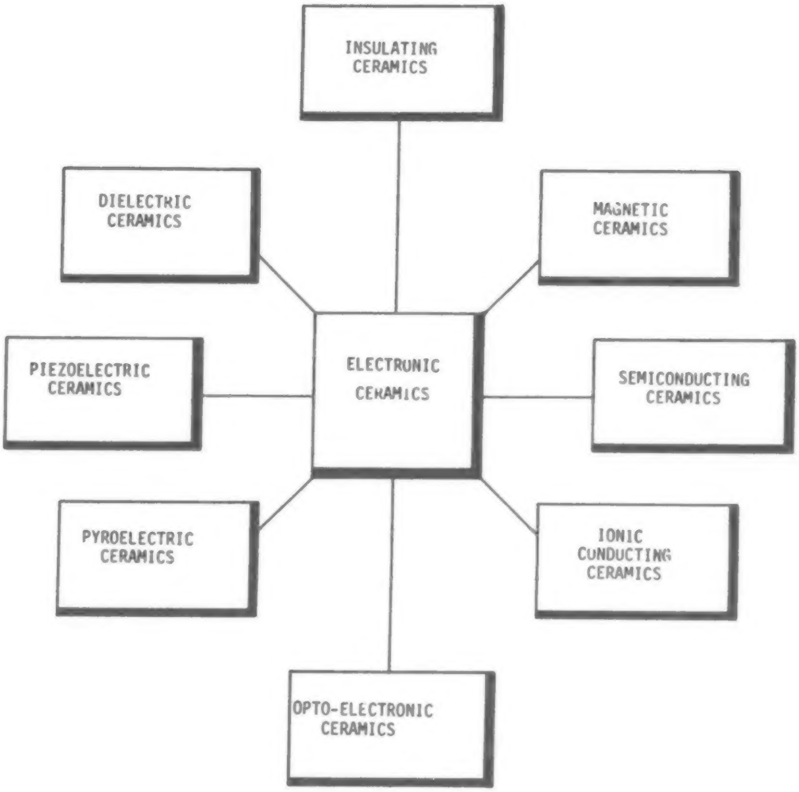

INSULATING CERAMICS
DIELECTRIC CERAMICS
MAGNETIC CERAMICS
PIEZOELECTRIC CERAMICS
ELECTRONIC CERAMICS
SEMICONDUCTING CERAMICS
PYROELECTRIC CERAMICS
IONIC CONDUCTING CERAMICS
OPTO-ELECTRONIC CERAMICS

FIGURE 19: Types of Electronic Ceramics

TABLE 8

Applications of Electronic Ceramics

Type	Properties	Material	Applications
Insulating	Non-Conducting	Al_2O_3, MgO, BeO	IC substrate, MLC Packaging Substrate for Hybrid Circuits, Capacitor & Resistor Substrate
Dielectric	Charge-Storage	$BaTiO_3$, $SrTiO_3$	Ceramic Capacitors, Microwave Filters, Trimmers
Piezoelectric	Interconversion of Electric-Mechanical Energy	PZT	Vibrators, Oscillators, Filters, Spark Generators, Surface Acoustic Wave Technology
Magnetic	Magnetic	$MnZnFe_2O4$ $Ba_6Fe_{12}O_{19}$	Magnetic Recording Head, Temperature Sensor, Permanent Magnet, TV Cores
			Speakers, Computer Peripherals, Magnetic Tapes
Opto Electronic	Optical-Electronic	Al_2O_3, PLZT, Y_2O_3	High Voltage Sodium Lamp, Optical Windows Laser Materials, Light Memory Element
		$LiNbO_3$	Video Display & Storage, Light Shutter & Valve, Communication
Pyroelectric	Infrared Sensitivity	SbSi + glass Sbsi + Polymers	Fire and Smoke Detectors, IR Detectors, Vidicons
Ionic Conductor	Ionic Mobility	Beta - Al_{O_3}	Sensors, Battery Separator
Semi Conductor	Electronic Mobility	$BaTiO_3$, SiC ZnO, V_2O_5 &	NTC Thermistor: Temperature Sensor Compensator PTC Thermistor: Heater Element, Temp. Controller CTR Thermistor: Heat Sensor Element Thick Film Thermistor: Infrared Sensor Varistor: Noise Elimination

the electronics circuitry, and to increase communication speeds. Significant developments in material and process technologies have taken place to accommodate these changes. Nevertheless, considerable scope exists for improvements, and active work is in progress to achieve these, particularly in the USA and Japan.

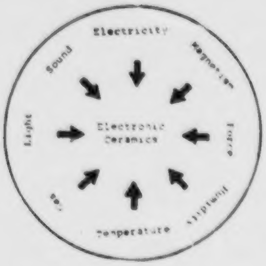
4.4.2 Current Status and Outlook

Japan is considered to be the world leader in both the technology of electronic ceramics and in the manufacture of components and integrated circuits. Multi-layer circuits (MLC) are taking over from older types of circuitry, and intense competition exists for developing materials with the required properties and the technology to process and manufacture them. US industry is taking steps to protect its domestic share of the market and, if possible, to increase it. Competition should push the future search for advances in MLC technology toward three basic goals: reductions in cost; improvements in reliability; and compatibility with future generations of integrated circuits.

Two areas of application which have been identified as having the greatest market potential are integrated optics and sensors.

Integrated optic circuits are optical waveguides that perform a variety of processing functions on the light beams that they guide. The largest end use for integrated optics will be in fibre optic communications systems, including commercial telecommunications, military communications, and computer-to-computer data communication links. Other potential end uses include optical sensing, optical signal processing, and optical computing. In the near future, these devices are expected to be manufactured using single-crystal ceramic materials, such as lithium niobate as a substrate, because of their electro-optic properties and ease of fabrication. Eventually semiconductor materials such as gallium arsenide may be preferred. Although these devices offer the potential for significant performance and cost-saving benefits in the fibre optics systems, a number of technical barriers exist which must be overcome before commercial acceptance and market opportunities arise. Virtually all activity in this area at the present time is in research and development. A number of countries are active in this area, particularly the USA, Japan, France and the United Kingdom. Market production is expected to be around $900 million in the USA alone in the 1990s.

Ceramic sensors are also expected to provide a large market in the coming decade because of the wide range of potential applications. These arise from the fact that electronic ceramics are sensitive to, and can therefore detect, a number of different signals as shown below:



Ceramic sensors for the detection of combustible gases appear to be especially promising for the future. Both the USA and Japan are active in this area. These sensors are based on porous semiconducting oxides such as tin, lead and zinc oxides. The electrical conductivity of these materials responds to the presence and concentration of various gases. Gas sensors are used or will be in use for a number of applications, in both name and industry. These include environmental monitoring and control, process control, and energy management. Toxic and combustible gas-monitoring is used in a variety of industries, including oil and gas drilling, refining, power generation, and the chemical and petrochemical processing industries.

The use of gas-monitoring devices is quite common in the US industry for toxic gas-sensing applications, but relatively little is used for combustible gas-sensing applications. In Japan, however, it is reported that gas sensors are heavily used in combustible gas applications, particularly as gas leak monitors are in the home. Growth rates of about 40 to 60 percent have been reported.

Indications are that a number of major potential applications for ceramic gas sensors will be realized in the coming decade. These include furnace monitoring, carbon monoxide monitoring, automobile exhaust monitoring (for gases other than oxygen), and process control. Should both the necessary technological advances and the commercial diffusion into some of these applications take place, the growth in industry sales is expected to rise by 40 to 50 percent annually. World sales could rise to $260-450 million.

4.5 Industrial Products

Industrial application of advanced ceramics is fast becoming a very important area of growth. First, the manufacturers of these products are trying to recover, at least partially, the cost of their investment in R & D. Some of these companies have invested substantial sums of money over the last five to 10 years for developing the materials and the manufacturing technology for the components for automobile engine applications. However, for reasons discussed elsewhere in this report, the market for these products has not developed as originally anticipated. For business reasons, the manufacturers are very actively seeking applications for which there is an immediate market.

Second, and more important, the advanced ceramics developed for engine applications have good properties, including mechanical strength at high temperatures and resistance to erosion. They can satisfy the needs of a number of industries which have need for better performing materials because of technological changes and improvements (i.e., the needs of industry for better performing materials happens to coincide with the needs of the advanced ceramics industry for an immediate market).

The industrial applications can be grouped into two categories: manufacturing and machinery industries; and process industries (chemical, iron and steel, aluminum and other non-ferrous metals) and semiconducting processing.

Some typical examples of industrial uses for advanced ceramics are listed in Table 9.

4.6 Energy and Space Products

The good thermal, mechanical and chemical resistance properties of advanced ceramics are advantageous for a number of uses in energy generation and conservation applications, as well as in the aerospace industry, particularly space vehicles.

4.7 Consumer Products

Advanced ceramics are being used for the manufacture of a number of consumer products, particularly in Japan, including knives, scissors, components for electric razors, golf clubs, skates and fishing rods. This market is expected to grow substantially in the immediate future.

TABLE 9

Industrial Products Made from Advanced Ceramics

Manufacturing & Machinery Uses

- Mechanical Seal Rings
- Bearings
- Valves
- Extrusion & Wire Drawing Die Inserts
- Liners and Valves for Industrial Pumps
- Components for Mechanical Handling Equipment
- Textile Guides

Process Industries

- High Temperature Gas Fans
- Heat Exchanger Tubes and Radiant Tubes
- Skid Buttons for Steel Reheating Furnaces
- Welding Nozzles and Insulators
- Non-Ferrous Foundry, particularly Aluminum (thermocouple sheaths, riser stalks, crucibles, furnace tapping seats and plugs etc.)
- Precision Jigs and Fixtures for Soldering, Brazing and Heat Treatment Processes
- Stable Wear-Resistant Fixtures for Electrochemical Processing
- Chemical Manufacturing Equipment
- Burner parts (pulverized coal)
- Nozzles for Sand Blasting
- Ceramic Heaters
- Molds for High-Temperature Annealing
- Crucibles for Melting Corrosive Alloys and Metals

5. MARKET POTENTIAL AND OUTLOOK

5.1 General

Although the need for advanced ceramics for a number of applications with large market potential is well established, and some success has been achieved in penetrating the markets a reliable, long-term market potential is difficult to determine. The technologies are not yet fully developed, and solutions to a number of technical barriers are not clear, particularly how long they will take to bring about. In some cases, these barriers are severe enough to retard commercialization (e.g., engines) and in other cases, commercialization has already occurred but the barriers serve to limit market penetration (e.g., cutting tools). Also, the severity of the barriers, and therefore the timing of their removal, applies to across the anticipated application areas.

In addition, market penetration depends on the relative merits of competing technologies, particularly cost. In the majority of cases, advanced ceramics will be competing against well established metals and metal technology and, therefore, market penetration will depend on a trade-off between performance and cost. The market forces in the end will determine the outcome.

A number of studies for the USA and Japan are available and will briefly be reviewed.

5.2 Market Data for the United States

Kenney and Bowen were the first to recognize the importance of market potential data in creating interest in advanced ceramics, and, more important, to point out the international opportunities and competition. Their study reviews the advanced ceramics market in Japan and compares it with the world market. The data for Japan were obtained from the Yano report; data for the USA and Europe from trade literature and personal discussions with industry representatives. A comparison of the advanced ceramics market for Japan and the world (compiled by Kenney and Bowen) is given in Table 10. The total world market for advanced ceramics was $4.25 billion, and almost half this demand was being met by Japanese companies. It is also important to recognize that the bulk of the market was in electronic ceramics (88 percent in electronic ceramics, compared with 12 percent in structural ceramics). This indicates that economic reasons for the growth of advanced ceramics were linked to the needs of the electronics and other high-technology industries. Since then, the growing market in structural ceramics for engine and other applications has been recognized. The world market data given in Table 11 was taken from Bowen. The detailed data base from which these figures were arrived at is not available.

TABLE 10

Comparison of High-Technology Ceramics Markets, 1980
(in Millions of Dollars)

Product	Japan+	World
Ceramic powders	$130	$250
Electronic IC packages/substrates	540	880
Capacitors	325	750
Piezoelectrics	295	325
Thermistors/varistors	125	200
Ferrites	380	480
Gas/Humidity sensors	5	45
Translucent ceramics	20	45
Cutting tools:		
carbide, cermet,	120	1000
coated noncarbide*	5	25
Structural ceramics (heat- and wear-resistant)	120	250
Totals	2065	4250

*For example, alumina, partially stabilized zirconia, silicon carbide and nitride, and oxynides.

+Ref, 1

(After Kenney and Bowen)

TABLE 11

Projection of World Market for Advanced Ceramics
(in Millions of Dollars)

	1980	1990	1995
Japan	1,900	6,500	9,000
USA	1,500	5,000	7,000
Other	700	500	1,000
Free World Total	4,100	12,000	17,000

(After H.K. Bowen)

Considerable discrepancy exists between Bowen's data and other sources for the US and world markets. One possible reason is the method used (i.e., whether the data are based on the 'raw' advanced ceramic or on the value of the 'finished' ceramic). In the case of hybrid circuits, for example, two values can be used: the value of the substrate, and other ceramic materials used in making the hybrid circuit. This will be considerably smaller than the value of the completed units which includes processing and testing costs.

Recently Shroff of SRI International conducted a detailed study of the market potential, technology status and timeframe for market penetration of advanced structural ceramics: "We agree that the long-term outlook for advanced ceramics is exciting - what we question is the timing of commercialization." SRI forecasts a 1995 world market of about $1 billion for structural ceramic materials.

Johnson et al. of Argonne National Laboratory, have conducted a detailed analysis and assessment of the economic implications of the structural ceramics industry in the USA. The study was supported by the Department of Energy. The market potential was obtained by estimating 1981 sales of the conventional-materials parts that could be replaced by ceramic parts. Most of the shipment value data for the conventional parts was obtained from the 1977 Census of Manufacturers, issued in 1980. The sales were projected to the year 2005, using the growth rates of industries from the DRI TRENDLONG-20007B Scenario. The ceramic market potential for the years 1981, 1990 and 2000 by specific applications were calculated and these data are given in Table 12. The total market potential was projected to increase from $4.3 billion in 1981 to $10.9 billion by the year 2000. This corresponds to an annual average growth rate of 6.0 percent in the decade 1981-1990 and 4.2 percent for 1990-2000 period.

To arrive at market penetration of any new technology, the competitive aspects of the technology must be considered (i.e., the new technology has to compete economically if it expects to get a share of the market from other technologies). Since the data were not available, survey analysis methodology was used to estimate market penetration. Industry sources provided anticipated market penetration data for various applications and conditions by the year 2000. Most industry experts believed that only a very small fraction of the market potential could be captured without significant government assistance for the basic research necessary to overcome the technological barriers.

The range of market penetration estimates arrived at are given in Table 13. The low penetration estimates little or no government funding for ceramic research, and it is expected that only 5 percent of the total market will be penetrated for various applications. Industry sources, however, believe that a determined effort spurred by government funding for ceramic research can lead to commercialization by the late 1980s and 1990s. Under this

TABLE 12

Summary of Market Potential for Selected Ceramic Parts for US (Millions of 1981 Dollars)

Applications	Market Potential 1977	1981	1990	2000
Diesel/gas turbine components for highway vehicles				
Pistons, piston rings, and valves	595	709	1,199	1,807
Cylinder liners & cylinder head inserts	653	778	1,316	1,984
Bearings				
Taper rollers, nontaper rollers, mounted bearings, rollers and spare parts	2,099	2,502	4,232	6,379
Turbochargers	101	120	203	306
Gas turbines, except aircraft	148	176	298	449
Total for all applications	3,596	4,285	7,248	10,925

TABLE 13

A Range of Market Penetration for Ceramic Components by the Year 2000 for US (Millions of 1981 Dollars)

Applications	Market Potential	Market Penetration (%)		Market Penetration	
		Low	High	Low	High
Diesel/gas turbine components					
Pistons, piston rings, valves[a]	1,807	0.05	0.20	90	361
Cylinder liners, head inserts[a]	1,984	0.05	0.20	99	397
Bearings	6,379	0.05	0.30	319	1,913
Turbochargers	306	0.05	0.75	15	230
Gas turbines, except aircraft	449	0.05	0.30	22	135
Total	10,925			545	3,036

[a] Includes gasoline and diesel engine parts for all applications.

(Source: L.R. Johnson et al.)

high-penetration scenario, the market penetration could be 20 to 30 percent for most of the applications by the year 2000, and up to 75 percent for the turbocharger applications.

The relationship between market penetration and market potential for these low and high cases is given in Figure 20. It was assumed that the ceramic market penetration begins in 1985 for diesel engines larger than 200 hp (truck and stationary), bearings and turbochargers. Subsequently, with the demonstration of technology in the market place, the ceramics were assumed to begin by 1990 to penetrate the more complex markets of small diesel engines (200 hp), adiabatic diesel engines, automobile diesel engines, gas turbines and stationary gas turbine engines.

Under the 'low' scenario, the total market penetration by the year 2000 is estimated to approach $545 million (1981 $). For the 'high' scenario, this penetration would be about $3 billion.

The US Commerce Department study entitled "A Competitive Assessment of the US Advanced Ceramics Industry" (published in March 1984), provides the most up-to-date market projection, and perhaps the most reliable data for the US market. The projected shipments of advanced ceramics by the year 2000 are given in Table 14. The electronics ceramics are expected to grow from $534 million in 1980 to $3,485 million in 2000: the cutting tools from $45 million to $960 million: engine parts from zero in 1980 to 840 million; and wear parts from $20 million to $540 million.

5.3 Market Data for Japan

Market data for Japan are available from a number of sources listed below:

- Yano Research Institute
- Ministry of International Trade & Industry (MITI)
- The Long-Term Credit Bank of Japan, Ltd.
- Mitsubishi Bank
- Toshiba Corporation
- National Economic Research Association
- Yano Research Institute Data

Yano Research Institute, Tokyo, published a report entitled "New Ceramics Market in Japan" (August 1982). It is a comprehensive study of the Japanese advanced ceramics industry, covering 48 companies engaged in advanced ceramics production and research. In a more recent report, the coverage has been increased to 89 companies in conformity with the classification adopted by MITI for fine ceramics. The market size data for advanced ceramics for 1980 and 1982 are compared in Table 15. The data for 1983 are given in Table 16.

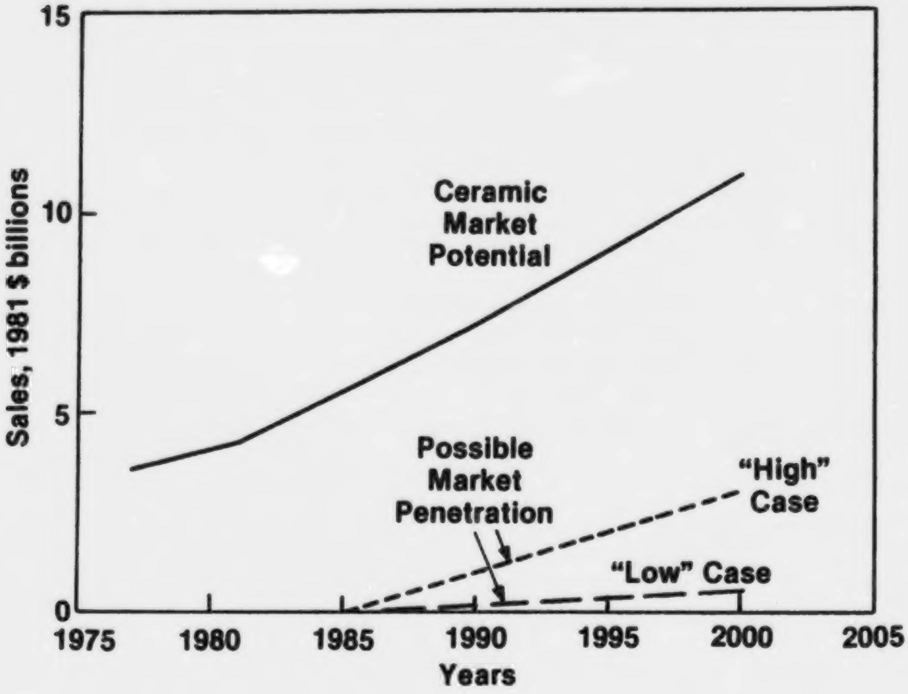


FIGURE 20: Market Penetration for Ceramic Applications under Alternative Cases

(Source: L.R. Johnson et al.)

TABLE 14

US Shipments of Advanced Ceramics by End Use to the Year 2000 (Millions of 1980 dollars)

End Use	1980	%	1990	%	2000	%
Electronics	534	88	1,900	75	3,485	59
Cutting	45	7.5	380	15	960	16
Wear Parts	20	3	180	7	540	9
Heat Engines	0	0	56	2	840	15
Other	2	0.5	15	1	70	1
TOTAL	601	100	2,531	100	5,895	100

(Source: Industry Analysis Division, US Department of Commerce)

TABLE 15

Market Size of Fine Ceramics in Japan for 1980 and 1982

Field/Product	Market 1980	Billions of Yen (millions of $) 1982	Difference between 1980 and 1982
Electronics			
IC Packages	68 (272)	86 (344)	none
Substrates	40 (160)	7.5 (30)	total manufactured goods in 1980, but alumina only in 1982
Capacitors	72 (288)	92 (368)	none
Piezoelectrics	65 (260)	38 (152)	no quartz resonators in 1982
Thermistors and Varistors	27 (108)	24 (96)	none
Gas Sensors	1 (4)	5.3 (21.2)	no humidity sensors in 1980
Ferrites	85 (340)	97 (388)	none
Translucent Ceramics	4 (16)	2.5 (10)	silica and sapphire in 1980, but only alumina in 1982
Heating Elements	2 (8)	3 (12)	none
Industrial Machinery Only			
Cutting Tools	12 (48)	14.7 (58.8)	none
Wear- and Abrasion-Resistant Materials	7 (28)	19.6 (78.4)	SiC, Si_3N_4, ZrO_2, BN, steatite in 1980, but alumina only in 1982
Heat-Resistant Materials	9 (36)		
Catalyst Carriers for Automobiles	8 (32)	10 (40)	none
Other			
Artificial Tooth Roots		1.3 (5.2)	none
Artificial Bone			none
Jewelry		9 (36)	none
TOTAL		400 (1600)	409.9 (1639)

(Source: American Ceramics Society)

TABLE 16

Projected Market Data for Fine Ceramics for 1983
(Millions of Yen)

Product	1982 Sales	Increase over 1981	1983 Sales	Increase over 1982
IC Packages	85 500	+25.7%	101 800	+19.1%
Ceramic Substrates	4 570	+1.8%	5 000	+9.4%
Capacitors	89 280	+10.8%	107 060	+19.9%
Piezoelectrics	30 822	+6.0%	45 690	+9.8%
Thermistors	15 849	+13.0%	19 318	+21.0%
Varistors	7 726	+5.0%	9 350	+21.0%
Sensors (ZrO_2)				
automotive industrial	4 646	+38.0%	5 690	+22.0%
Ferrites				
soft	59 594	-6.0%	69 500	+16.0%
hard	36 999	-6.0%	43 300	+17.0%
Cutting Tools				
ceramic	1 072	-18.7%		
cermet	4 412	+17.4%		
coating	8 294	-7.4%		
Wear-Resistant Alumina	19 568	+17.0%	20 214	+3.0%
Honeycomb Ceramic	9 300	+30.0%	10 700	+9.0%
Bioceramics	1 780	+132.0%	2 700	+51.0%
TOTAL	318 372		440 452	+38.3%

(Source: American Ceramics Society)

The Fine Ceramics Working Group (an advisory body to the Consumer Goods Industry Bureau, MITI), released a report in May which forecasts the market for advanced ceramics in Japan. The report identifies the following estimates:

	Estimated Market	
Year	Yen (trillions)	Dollars (billion)
1988	1	4
1990	1.3 to 1.8	5.2 to 7.2
2000	2.8 to 4.2	11.2 to 16.8

(Exchange Rate 1$ = 250 Yen)

MITI officials have indicated that about 75-80 percent of the above market for advanced ceramics is based on the requirements in the functional ceramics market, leaving about 20-25 percent for the structural ceramics market. This indicates the following breakdown.

Year	Functional Ceramics	Structural Ceramics
	(Billions of Dollars)	
1988	3	1
1990	3.9 to 5.4	1.3 to 1.8
2000	8.4 to 12.6	2.8 to 4.2

MITI officials have also indicated that the projected estimates for 1985 are following the upper curve (Figure 21), suggesting that the market size in the year 2000 will be much closer to $16.8 billion than to the lower figure of $11.2 billion.

A comparison of the market estimates from various sources is given in Table 17. It indicates that the projections are reasonably consistent, given the timeframe and technical uncertainties.

If one looks only at the advanced structural ceramics market, the bulk of it to date is in cutting tools, wear parts and catalyst carriers for automobiles. For 1982, the actual markets were, respectively, $58.8, $78.4 and $40 million (Table 16), totalling about $177 million. Advanced ceramics for engines had no market in 1982. According to MITI projections, structural ceramics have to increase from about $ 200 million in 1982 to $1 billion in 1988 - a five-fold increase. Given the technological problems, manufacturing cost, and market penetration, this estimate appears to be over-optimistic.

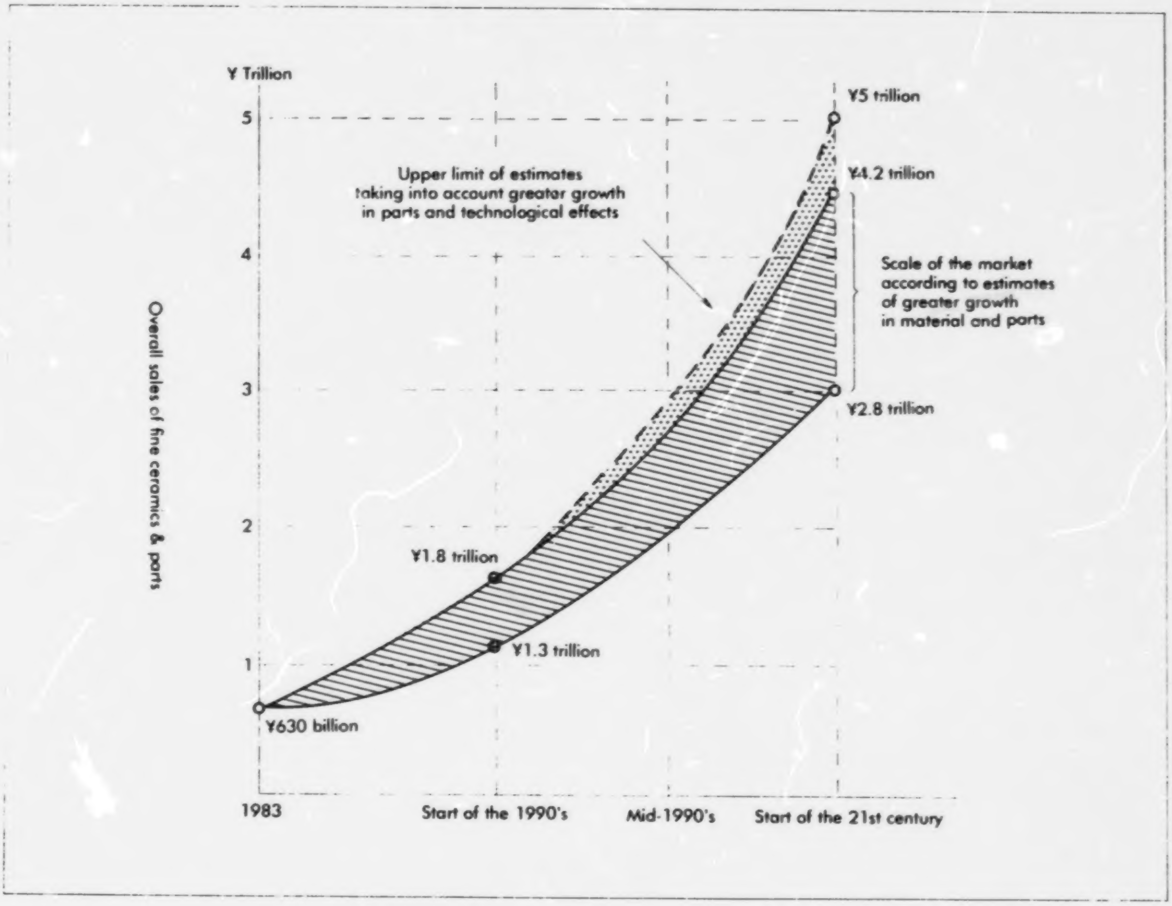


FIGURE 21: MITI Market Projection Data for Advanced Ceramics in Japan

TABLE 17

Forecasts of the Size of the Fine Ceramics Market in Japan (after The Long-Term Credit Bank of Japan, Ltd.)

(Unit: convert to billions of yen)

Organization / Application		1981	1990				Early 2000s
		*1) MITI survey	*2) Mitsubishi Bank forecast	*3) National Economic Research Association forecast	*4) Toshiba forecast	LTCB forecast	*5) MITI forecast
Electrical and electronic parts		189.8	535.0	669.5 to 799.6	664 to 759	540 or more	2,800 to 4,200 (But, considering the high growth rate in parts and the effects of the spread of technology, the upper limit on the forecasted size of the market is 5 trillion yen.)
Mechanical parts		40.8	143.0	279.4 to 979.4	266.8 to 920	210	
Transportation machinery (automobiles)	Engines	(non-gas catalyst carriers) 3.5	500			280 to 420	
	(Spark plugs)	37.0	52			52	
Nuclear power		25.0	70	339 to 469		59 to 88	
(Refractory materials)		-	60		322 to 448.5	-	
Biochemical		1		-	920 or more	100 to	
Total		About 300	1,360.0	1,287.4 to 2,248	2152.8 to 3047.5	1,241 to 1,410	

Notes: *1) "Fine Ceramics Data", MITI Fine Ceramics Office, November 1982

*2) from Mitsubishi Bank Survey Monthly Report No. 338 (June 1983), p. 25, Table 5, case (2)

*3) from "Industry Trends", National Economic Research Association, February 1983, p. 34, Table 3

*4) "Ceramic Industry", Vol. 121, No. 6, December 1983 (figures converted at the rate of $1 = 230 yen)

*5) "Fine Ceramics Basic Issues Conference Report", Fine Ceramics Basic Issues Conference

Another difficulty is in breaking down the Japanese market data in terms of Japanese domestic consumption and export. MITI officials indicate that the figures are based on total Japanese sales. Since these include both domestic and export figures, it is important to recognize that roughly 50 percent of world markets were supplied by Japan in 1980, and that they hope to maintain this ratio in the future. If this is accepted, then the projection $1.2-1.8 billion appears to be realistic.

In general, there appears to be little uncertainity in projecting markets for functional ceramics (e.g., electronics ceramics, bioceramics). For structural ceramics, particularly for heat engine applications, the market data should be considered as optimistic projections. Some scientific and technical experts believe that the technological problems and their impact on projected markets are too optimistic, given the seriousness of the issues involved. It appears that the 'ceramic engine' is a vision which may or may not be attainable. What is certain, however, is that ceramic parts and components will find applications in engines at an increased rate. The timeframe for the introduction of advanced structural ceramics in various market areas is given in Figure 22. Several authoritative sources suggest that market projection data should be followed on an annual basis, in the light of technical achievements made. Given this, a more realistic and reliable picture will emerge by 1990.

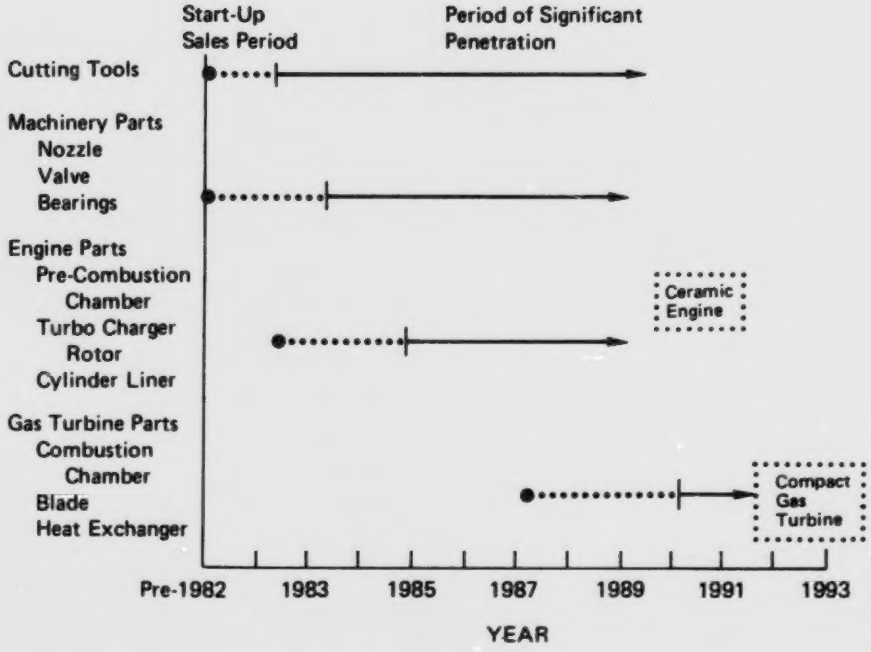


FIGURE 22: Timeframe for the Introduction of Advanced Structural Ceramic Components

(Source: US National Academy of Sciences)

6. INTERNATIONAL PERSPECTIVE

6.1 General

Because of the large market potential, estimated to be about $30 billion by the year 2010, and the indirect socio-economic benefits due to higher productivity and energy cost savings, estimated to be about twice as much, there is intense international competition for the development of advanced ceramic technology and its diffusion into the market place. The bulk of the market and indirect benefits are attributed to the 'structural' ceramic portion of advanced ceramics. Extensive research, development and commercialization programs are in place all over the world, addressing this area of advanced ceramics. Since the R & D programs are generic in nature - dealing with microstructural control of properties and process development - the results are expected to have an impact on the whole area of advanced ceramics and their varied applications.

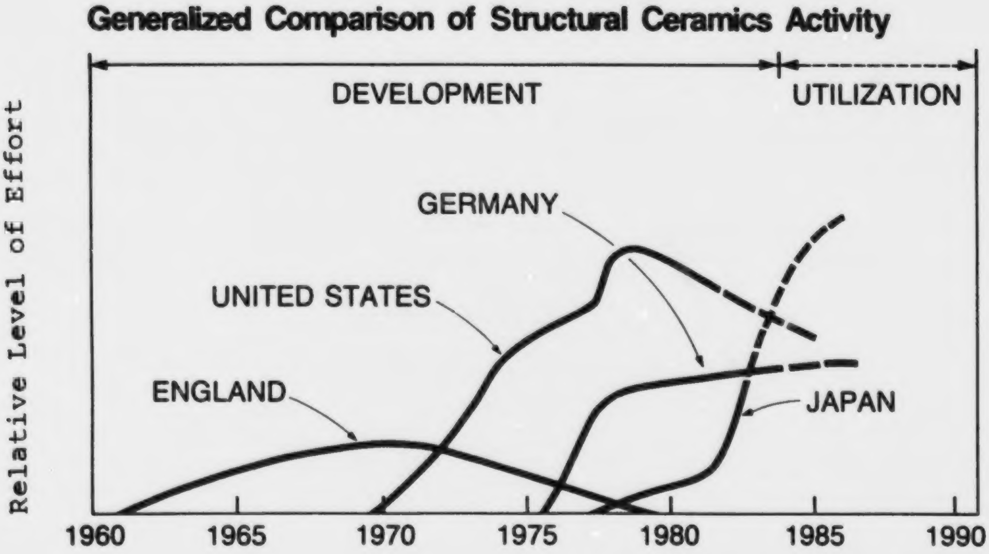
The following countries are in the fore front of research, development and commercialization because of joint industry-government initiatives:

- United States
- Japan
- West Germany
- Sweden

The relative level of effort in the UK, United States, West Germany and Japan in the period 1960 - 1985 is given in Figure 23.

A comparison of the present international R & D efforts in advanced ceramics, by application area, is given in Table 18.

Active studies on advanced structural ceramics came out mainly in the USA from the early 1970s, followed by West Germany and Sweden. Japan had a delayed start; advanced structural ceramic R & D studies did not begin until about 1978. However, today they are world leaders, as demonstrated by the fact that their materials are superior and their processing technology much closer to production than in other countries. Also, they have a number of engines made of ceramic components which are used to get experience for future commercialization. The Japanese are apparently willing to invest more in, and wait longer for, an emerging technology/industry to develop and become profitable than are companies in the USA and Western Europe. Japan is spending the most - in term of money and scientific and technical manpower - on advanced ceramics, structural as well as functional. The USA appears to be devoting more resources to this than Western Europe, but significantly less than Japan.



Source: L.R. Johnson, et al. "A Structural Ceramics Research Program: A Preliminary Economic Analysis"

FIGURE 23: Relative International Level of Effort in the Development of Advanced Structural Ceramics.

(Source: L.R. Johnson et al.)

TABLE 18

Present International R & D Efforts in Advanced Ceramics by Application Area (1984)

Application	Location United States	Japan	Western Europe
Electronic: multilayer capacitors	$10 to $15 million/yr	R & D spending unknown; said to hold 10:1 lead over USA in number of patents and engineers	Not estimated
Gas sensors	No more than $1 to $2 million/yr	R & D spending unknown; said to hold 3:1 lead over USA in number of technical papers; and 10:1 lead in patenting	Probably similar to USA level
Structural: heat engines	$35 to $40 million/yr	Greater than $50 million/yr	Less than USA; Germany and Sweden are the European leaders
Cutting tools	Probably no more than $1 million/yr	R & D spending unknown; 20:1 lead over US patents for period 1973 to 1982	Probably more than USA; West Germany alone nearly even with the USA in patents for period 1973 - 1982
Optical: integrated optics	Approximately $10 million/yr	Slightly less than US expenditures	About half of US expenditures

(Source: Charles River Associates, 1984)

Moreover, the Japanese effort would appear to be more organized toward achieving future industrial targets. Their effort is comprehensive; building on their existing dominance in the supply of ceramic powders for advanced engineering ceramics, and continuing through the product design and manufacturing process.

Future international competitiveness in advanced structural ceramics for engineering applications will be determined largely by the basic materials research and production engineering development now under way in different countries.

From an internationally competitive point of view, advanced ceramics are obviously of great importance to a national strategy, because this field of advanced technology also forms the base for many high-technology industries. Because of the high degree and depth of technology required, developments in this field are the focus of rivalry among the industrially advanced countries. Since 30 to 40 percent of the cost of such products goes into labour, products made in developing countries, where wages are relatively low, will have a price advantage that will make them internationally competitive. In advanced ceramics, as in the steel industry, near-developed countries may, in the future, take the lead in general purpose products. Japan and other countries advanced in this technology will be forced to shift their production to higher-grade, higher value-added products.

6.2 Advanced Ceramics in the United States

6.2.1 General

The United States has been the world leader in advanced ceramics - in research, development and commercialization - since the 1950s. Although the USA developed most of the scientific and technological innovations leading to advanced electronic ceramics, the commercial market leadership is now in the hands of Japan, currently supplying more than 70 percent of the world market. At present there is concern, both in industry and government, that in spite of scientific and technological leadership in advanced ceramics for 'structural' uses (e.g., automobile engines), commercialization is lagging, mainly because of the technological barriers still to be solved: reproducibility in manufacture, reliability in service, and competitive cost. There is also recognition that, as in Japan, commercialization should go hand in hand with technological development (i.e., applications should be developed for advanced ceramics, continuously matching technology development to market needs). American industry and governments have taken a number of new initiatives to regain leadership.

6.2.2 Government Programs, Policies and Initiatives

The principal driving forces for government support of R & D in advanced ceramics are:

- Perceived competition from Japan, West Germany and Sweden.
- The potential applications in defence products.
- National security considerations, including strategic material dependency and future space needs.

A number of departments and agencies of the US government support research and development on advanced ceramics. This work is carried out in in-house laboratories and on a contract basis in industry, universities and private research institutes and organizations. The government organizations, include: Department of Defence through the Defence Advanced Research Projects Agency (DARPA); agencies of the US Army, US Navy and US Air Force; Department of Energy; Department of Commerce, through the National Bureau of Standards; the National Aeronautics and Space Administration; and the National Science Foundation. The support of the latter organization is limited to R & D at universities.

The important position that advanced ceramic components hold today in the development of automobile engines and other high performance applications can be directly traced to the foresight, initiative and financial support given by DARPA to industry, beginning in the early 1970s. The OPEC oil embargo (1973) focused attention on energy conservation, dependence on oil imports and the need for using alternative fuels all of which required advanced ceramics. Because of this new motivation, the R & D programs were substantially expanded with financial support from the Department of Energy.

During the period between 1970 and 1982, the government supported a number of programs in industry to demonstrate the technical feasibility of using advanced ceramic components in the development of fuel-efficient and environmentally safe automobile engines. All but one were aimed at the development of gas turbine engines, (the exception being one program devoted to the development of diesel engines). The gas turbine work was carried out principally by three companies: Ford Motor Company, Detroit Diesel Allison Division of General Motors Corporation, and Garrett Corporation. The use of a gas turbine engine in a highway vehicle has been successfully demonstrated. The Cummins Engine Company has completed all the work on diesel engine development and has successfully demonstrated the performance of an adiabatic diesel engine, without a water cooling system, in a US Army five-ton truck.

At present the Department of Energy is supporting a fourth program focused on advanced gas turbine engines (AGT). Under this program the Detroit Diesel Allison Division of GM is developing the AGT-100 engine for incorporation into a 1985 Pontiac Phoenix X-body car. The Garrett Corporation, with support from the Ford Motor Company, is developing the AGT-101 engine for incorporation into the Ford family of cars. These are long-term programs (1982 - 1990) and results to date are very promising. The DOE budget for fiscal 1984 is $42.7 million (not including an allotment of $9 million for a national "Ceramic Technology Center for Advanced Engines", located at the Oak Ridge National Laboratory. The overall US government funding of advanced ceramics for engine development in the period between 1974 to 1982 is estimated to be about $140 million. (See Figure 24.)

Three recent studies have identified the need for a change in government policy, calling for a more directed support to promote the advanced ceramic industrial sector to counter international threats, particularly those posed by Japan. The Department of Energy study, which is based on the DRI annual model of the US economy, identifies the acroeconomic impacts (effects on gross national product, employment, fuel imports, and balance of trade) of US leadership in advanced ceramic components for automobile engines. The study recommends significantly higher government support for R & D.

Based on a competitive assessment study of the US advanced ceramic industry, the Department of Commerce has identified a number of options designed to push American industry ahead in advanced ceramics for automobile engine and other high-performance applications. The options can be grouped into two categories.

First, there are those designed to remove barriers for advancement of technology. These include increasing the federal R & D effort, as well as providing increased incentives directed towards increasing private industry R & D on advanced ceramics. The department has recognized that private industry is reluctant to commit the necessary substantial effort because of the long-term nature of the market. Other options in this category are: allowing anti-trust exemptions for cooperative industrial R & D, improving capacity to obtain and disseminate foreign scientific and technical information, and increasing educational opportunities and incentives for product design and manufacturing of advanced ceramic products.

Second, there are those options which help create or increase the market for advanced ceramics both domestically and for export. These options include: increased federal procurement of advanced ceramics for military, space and other governmental needs; use of federal regulatory policy to increase the market share for advanced ceramics; provide federal risk or liability insurance for manufacturers and users of advanced ceramics.

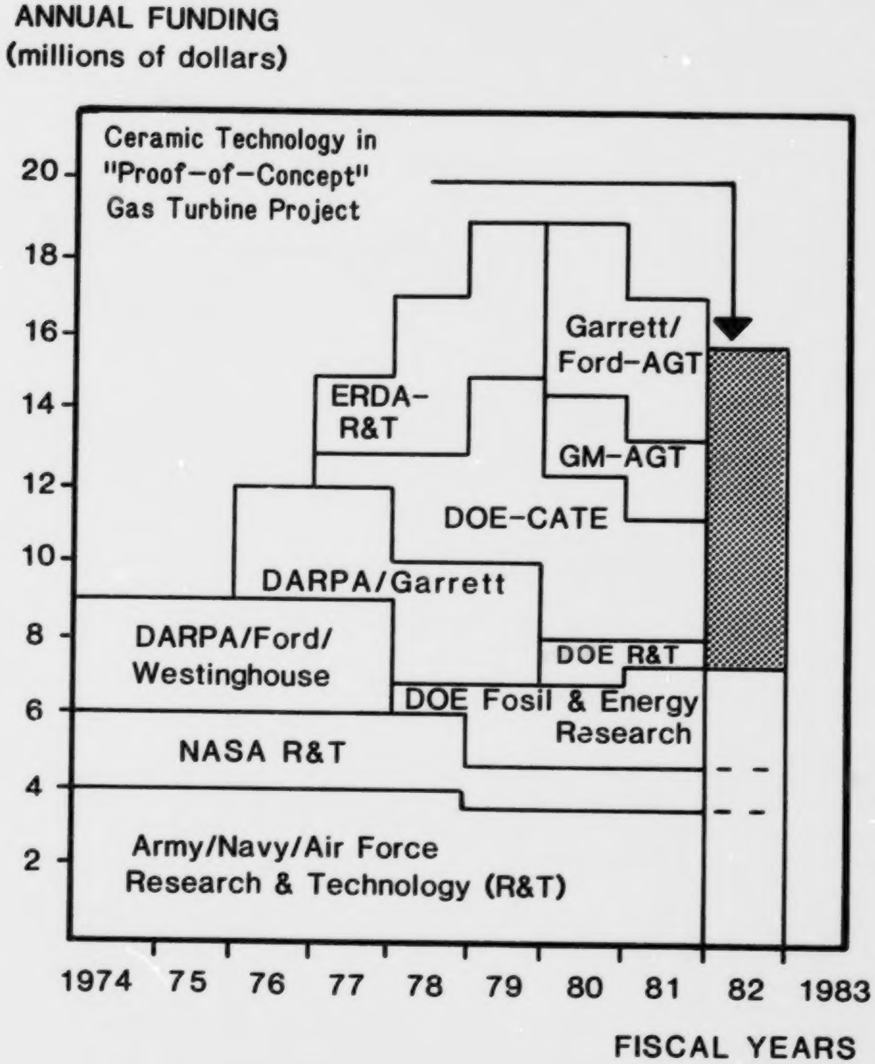


FIGURE 24: US Government Funding of Advanced Structural Ceramics Research and Development

(Source: Charles River Associates)

The US government is concerned about strategic materials because of their importance to defence needs, domestic economic well-being, and their international competitive position. In a recent study, the Office of Technology Assessment of the Congress of the United States, reached conclusions similar to those identified by the Department of Energy, discussed above.

To date, the only firm government action has been in enacting the National Critical Materials Act of 1984 (S.373) establishing a National Critical Materials Council under, and reporting to, the Executive Office of the President. This council has the responsibility for evaluating advanced technology needed for innovation and increased productivity within the basic and advanced materials industries, and recommending, wherever appropriate, the establishment of 'Centers for Industrial Technology'. Discussions with knowledgeable policy advisors indicate that it is very unlikely that the government will directly intervene in the market place to promote the advanced ceramics industry. However, precedence indicates that, if important, it will use defence procurement to promote R & D as well as market growth.

6.2.3 Industrial Activity in Advanced Ceramics

In 1980, the size of the US advanced ceramics industry totalled around $600 million in shipment value ($534 million from the electronic components business, and $65 million from the engineering products business). There were no commercial shipments of advanced ceramic engine components.

There are at least 50 major US companies active in the electronic component business, but many of them are fragmented into segments which produce only powders or specialize in a single component. For the most part, US companies are not as vertically integrated as their Japanese counterparts, where a few firms such as Kyocera, Murata and NGK Spark Plug dominate the production of advanced powders and a variety of electronic components. There are some US firms - IBM is the outstanding example - which are vertically integrated, but their production of advanced electronic ceramics (particularly integrated circuits) is a captive output which does not show up in trade data. Trade figures show that the USA has largely lost the electronic component business of the advanced ceramic industry to Japan. Although US firms appear to be holding their own in capacitor and resistor product lines, the integrated circuit market is in the hands of Japan.

Kyocera International, located in San Diego, California, accounts for about 70 percent of US shipments of integrated circuits. The electronic components business is considered to be relatively mature, but a low value-added commodity business.

There are about 50 major US firms engaged in R & D or limited commercial production of advanced engineering ceramics. Many of these are active in single, specialized product lines. There are 30 to 40 companies engaged in R & D on advanced ceramic engines. Market trends cannot be easily assessed because there has not yet been significant commercial production of advanced ceramic engineering products.

The major US firms engaged in advanced ceramics engineering products are listed in Table 19.

A number of companies which were not traditionally in the ceramic business are becoming involved in advanced ceramics. In some cases it is for taking advantage of new opportunities for diversification; in others, to meet the demand for requirements within the company. IBM, for example, is said to have invested more than $1 billion to set up a facility for in-house computer development. Some of the important non-traditional ceramic companies now actively participating in advanced ceramic R & D activities are:

- IBM
- W. R. Grace
- Standard Oil (Ohio)
- Allied Chemical
- Dow Corning
- Celanese
- Stauffer
- Garrett
- Alcoa
- Union Carbide
- ICI Americas
- Dow Chemical
- PPG Industries
- Cabot
- American Cyanamid
- Air Products & Chemicals

It is not possible to establish how much advanced engineering ceramics R & D is supported by US industry on its own, since such information is often considered proprietary or is buried in data for larger end products. Nationally, private industry supports about the same amount of R & D that the US federal government does. This would suggest a total national advanced ceramics R & D effort currently approaching $100 million. Of the 1800 US ceramics companies listed in the Bulletin of the American Ceramic Society (January 1983), it is estimated that 200 may be engaged in R & D on advanced ceramics. It is estimated that up to 1000 scientists and engineers are principally engaged in R & D on advanced ceramics, with perhaps 1000-2000 more peripherally involved. Using current average salaries and overhead rates, a national R & D effort approaching $100 million is projected.

Table 19

Major US Firms Engaged in Advanced Ceramic Engineering Products Research and Production

Cutting Tools	Wear Parts
Kennametal Inc.	Carborundum Co.
Carboloy Systems Dept.	General Electric Co.
GTE Walmet Co.	Norton Co.
Teledyne Firth Sterling	Coors Porcelain Co.
Coors Porcelain Co.	ESK Corporation
Valenite	ART Inc.
TRW/Wendt-Sonis	
Talide Metal Carbides Corp.	
Adams Carbide Corp.	
Babcock and Wilcox	

Heat Engine and Parts	
Engine Design and Development	Ceramic Materials and Parts
Ford Motor Co.	Carborundum Co.
Garret Corp.	Norton Co.
Cummins Engine Co.	Corning Glass Co.
General Motors Corp.	Coors Porcelain Co.
Westinghouse Electric Corp.	Ceramtech Inc.
General Electric Co.	GTE Sylvania
International Harvester	General Electric Co.
Hague International Co.	Kaman Sciences Corp.
Terratek Inc.	Dow-Corning Co.*
Caterpillar Tractor Co.	United Technologies Corp.
Pratt and Whitney Co.	Airesearch Casting Co.
	Ceradyne, Inc.
	DuPont*
	Celanese*

*Particularly strong in advanced ceramic composites/fibres R & D.

(Source: Industry Analysis Division, US Department of Commerce)

In 1980 the US ceramic industry, tradional as well as advanced, was a $50 billion industry. Over 100 of those companies on the "Fortune 500" list produce or process ceramics in some form.

6.2.4 Professional and Technical Societies

The American Ceramic Society is the official professional society that represents the entire ceramic community in the USA. This includes scientists, engineers and other technical people and industrial companies. It has more than 10,000 members and about 1800 companies in its directory. The society is divided into 11 divisions, five of which cover different aspects of advanced ceramics.

Another important society that plays an important role is the Materials Research Society. Only those who are involved in research are members of this society.

6.2.5 University Activities in Advanced Ceramics

A large number of universities in the USA are active in advanced ceramics R & D, and the number is growing rapidly. These include not only those with formal ceramic departments for educating scientists and engineers, but also others who carry out advanced ceramics R & D activities in other disciplines such as metallurgy and materials science, electrical engineering, physics and chemistry.

Some of the important universities are listed below:

- Massachussets Institute of Technology, Boston, Mass.
- New York State College of Ceramics, Alfred, NY
- North Carolina State University, Raleigh, NC
- Ohio State University, Columbus, Ohio
- Pennsylvania State University, University Park, Pa.
- Renesselar Polytechnic Institute, Troy, NY
- Rutgers, The State University of New Jersey, Piscataway, NJ
- University of California, Berkley, Calif.
- University of California, Los Angeles, Calif.
- University of Florida, Gainsville, Fl.
- University of Illinois, Urbana, Ill.
- University of Utah, Salt Lake City, Utah
- University of Washington, Seattle, Wash.

Recently, Rutgers University, with assistance from the National Research Council, Washington DC, started a "Center for Ceramics Research" as part of their expansion of the department of ceramics. It has more than 30 industrial members, with an annual fee of $30,000. The State of New Jersey, recognizing the importance of advanced ceramics as a base for other high-technology industries, has given about $5 million to support the facilities at the centre.

MIT has a similar centre for ceramic process development, with an industrial clientele of about 20.

It appears as though a number of new centres will come into existence in the coming years because interest in advanced ceramics is increasing both in industry and government.

6.3 Advanced Ceramics in Europe

6.3.1 General

Many countries in Europe are actively involved in research, development and commercialization of advanced ceramic materials and components. The motivating factors are: a desire to achieve energy efficiency in engines to reduce energy costs and dependence on imports; concern as to the availability and cost of imported strategic raw materials; concern regarding the impact of developments in the USA and Japan in advanced ceramics on domestic industries; and more important, recognition of the full potential of advanced ceramics to provide opportunities for their metal, chemical and manufacturing industries in the international market.

The countries that have substantial programs are West Germany, Sweden, the UK and France.

6.3.2 Advanced Ceramics in West Germany

West Germany completed a national R & D program between 1974 and 1983. It was designed to develop and commercialize advanced ceramic components for use in automotive engine and other high-performance applications. This was a cooperative program between government, industry, universities and research organizations, with a total funding of about DM 100 million. Government and industry shared the program cost on a 50-50 basis. The university-research institute cost, however, was fully funded by the government. Three engine manufacturers, seven ceramic manufacturers and seven research organizations participated in the program. The participants are listed in Table 20. The distribution of the funding among the participants is given in Table 21.

West Germany has launched a new 10-year program on advanced materials, with a budget allocation of DM 70 million for fiscal 1985. The areas comprise ceramics, powder metallurgy, compound materials (composites) and high-temperature materials. Another DM 14 million has been allocated for projects related to corrosion, tribology and wear. The exact amount for advanced ceramics is not clear, but appears to be quite significant.

The motivation for launching this huge 10-year program appears to be based on two factors. First, there is the recognition that advanced ceramic components will be successfully developed and exploited in the

Table 20

List of Industrial Participants in the West German National Program on Advanced Ceramics for Engines

Engine Manufacturers:

Volkswagen
Daimler Benz
MTU

Institutes and Universities

Max Planck - Institut, Stuttgart
T.U. Berlin
T.U. Clansthal - Zellerfield
IZFP Saarbrucken
T.U. Karlsruhe
Universitat Erlangen
DFVLR Koln

Ceramic Manufacturers:

Annawerk
Degussa
ESK
Feldmuhle
Sigri
H.C. Starck
Rosenthall

TABLE 21

Budget in West German National Program For the Period 1974 - 1980

(Thousands of DM)

	Part of BMFT	Total
Industry	29,686	59,372
Institutes	4,932	4,392
	34,618	64,304

(Source: E.M. Leone et al.)

future because of international commitment, particularly in the USA and Japan. Second, there is concern on the part of industry to protect the domestic market, based on their technologically competitive position gained to date; concern for saving energy cost and reducing dependence on strategic materials which are now being imported; concern for long-term threats to traditional industries - (particularly metal industries) posed by advanced ceramic materials in terms of GNP, jobs and other socio-economic issues.

In arriving at the programs for the 10-year plan, the ministry of science and technology has had extensive discussions with industry and universities. This program, therfore reflects the national goal and commitment of West Germany.

Significant achievements were accomplished in the first national program, both in the development of advanced ceramic components and their incorporation in automobile engines. H.C. Starck Company, a major world supplier, has developed the manufacturing technology for silicon nitride powders. The ceramic component manufacturers have developed manufacturing capabilities. However, reproducibility in manufacturing, reliability in service, and cost are still important problems. For example, Electroschmeltzwerk Kempten (ESK) has developed the manufacturing capability for silicon carbide components for automobile engine applications, but finds that commercial markets are still a number of years away. SIGRI, on the other hand, is concentrating on developing non-automobile applications, such as heat exchangers, abrasion- and corrosion-resistant products for the immediate term. Feldmuhle, however, is already successfully marketing advanced cutting tools made of silicon nitride.

A number of changes in the interest of ceramic companies originally involved in the development of advanced ceramic components are evident. For example, Degussa has stopped participation, perhaps because the market opportunities were too far in the future. Rosenthall has divested its technical products division to a joint venture with Hoecht because of the burden of carrying on R & D in an area where the market cannot share the cost in the immediate term.

It is also evident that a number of larger companies are showing interest in participating in the long-term potential associated with the advanced ceramics market. Bayer is setting up facilities for the manufacuture of ceramic powders. Hoecht, through Rosenthall, is establishing its presence in the market place. Siemens, one of the largest companies in Germany in the manufacture of electronic ceramics, seems to be limiting its activity to the existing market area.

Both Daimler Benz and Volkswagen have developed gas turbine engines for automobile and other vehicular applications. However, the former is ahead in the demonstration of the engines in vehicles. The company appears to have confidence in this application on a long-term basis, and is continuing the work on gas turbine engines (as well as other applications for gasoline engines, such as turbochargers). Daimler Benz is one of the largest truck manufacturers, and sees an opportunity for gas turbine engines in them. Defence needs are also in the background, particularly for tanks.

Volkswagen, on the other hand, is cautious about the role of the gas turbine engine for application in small cars and vehicles - its primary market. It is investigating the use of advanced ceramic components for its existing engine types - both gasoline and diesel - and is confident that a number of beneficial uses can be found. It has a substantial in-house effort to monitor the developments in advanced ceramic components, and is likely to take advantage of opportunities as they arise. Ceramic turbochargers and components for diesel engines appear to be high on the list.

6.3.3 Advanced Ceramics in Sweden

6.3.3.1 General

Next to Germany, Sweden is the most active country in Europe involved in the development of advanced ceramics for engine applications. As shown by the data given below, the ceramic industry in Sweden is relatively small. However, these figures apply only to the specific product lines. The companies otherwise belong to much larger units with large development budgets. It is quite likely that these big companies are interested in exploiting the long-range economic potential of advanced ceramics.

Company	Product Lines	Turnover ($ Millions)	Employees
Ifo	Electrotechnical Sanitary Enamel	70	1500
Gustavsberg	Sanitary Household Enamel Brick-works	70	1300
Hoganas	Building Refractory Brick-works	60	900
Rorstrand	Household	20	650
Forshammars Bergverk	Refractory	18	200

It is more likely, however, that the Swedish interest is related to its rather important and viable automobile industry, which plays a very important role in Swedish employment and balance of trade. Volvo, which is an internationally known company, manufactures its own cars, trucks, buses and boats. SAAB-SCANIA, another important vehicle manufacturer, also plays a very significant role in providing jobs and balance of payment advantages. Volvo Flymotor manufactures jet engines for Swedish fighter planes and is also involved in international cooperation on civilian jet engines.

Stal Laval develops and manufactures gas and steam turbines for power generation, industrial use and ship propulsion.

United Turbine, which is a subsidiary of Volvo, is engaged in the development of a small automobile gas turbine engine. United Stirling belongs to a government-owned section of the industry and is developing Stirling engines for different applications, such as total energy systems and small delivery vans.

6.3.3.2 Swedish National Program

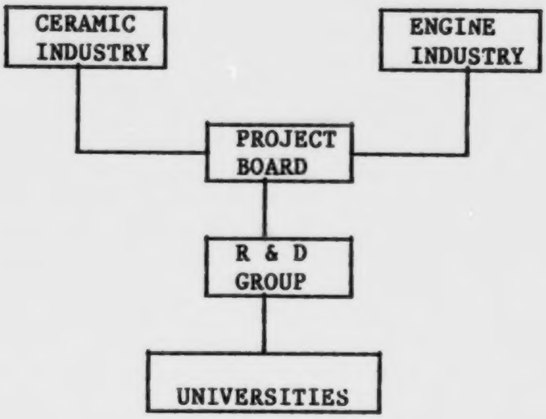
Recognizing the importance of taking the lead in developing advanced energy efficient engines to protect the interest of the Swedish automobile and engine manufacturers, the Swedish Board of Technical Development (STU), a government agency, decided to financially support the work in advanced ceramic materials for heat engine applications in 1976. The timing appears to indicate that the STU followed developments in the USA and Germany quite closely and came to the conclusion that it was in the best interest of Swedes to initiate their own national program. This would enable them to protect their competitive position, both in export potential and in the domestic industry and markets.

The STU decided to support two parallel activities - one aimed at materials development and the other at engine development.

The long-term goal of the materials development program was to promote and facilitate domestic production of ceramic engine components. The development work was assigned to the Swedish Institute for Silicate Research in Trondheim.

The task of designing engines and introducing ceramic components into the engines was assigned to engine and vehicle manufacturers. Financial support to these companies was provided so that engine manufacturers could obtain necessary ceramic components from abroad. This allowed early development of the technology before the Swedish ceramic industry could produce the parts domestically.

The organizational structure used for the management of the program is shown below:



The work of the ceramic R & D group was guided by a project board consisting of representatives from the ceramic industry, engine manufacturers and universities. This ensured a close cooperation between the R & D group and industry. For example, the engine manufacturers could present the specifications for engine components to meet their needs, providing important guidelines for the work. Also, the R & D group could assist the engine industry in the characterization of components purchased from outside suppliers. The industrial companies that participated in the national program are listed below:

AB Fordhammars Bergverk, Goteberg
AB Gustavsberg, Division Porslin, Gustavsberg
AB Sandvik Hard Materials, Stockholm
AB Volvo, Goteberg
ASEA Ceram
Hoganas-Keramik AB, Hoganas
Ifo Electric AB, Bromolla
KemaNord Industrikemi AB, Ljungaverk
Rorstrand AB, Lidkoping
Saab-Scania AB, Sodertalje
United Stirling AB, Goteborg
United Turbine AB, Malmo
Volvo Flygmotor AB, Trollhattan

Details of R & D programs within the companies are not available. However, a detailed description of the work carried out at the Swedish Institute for Silicate Research (Svenska Silikatforsknings Institute) is available. (See Figure 25). The Institute has a staff of about 15, of which five work on the high-performance ceramics program for engines. The original program, started in 1976, is being continued. The duration of the current program is 1984-1987, with an annual budget of approximately $800,000.

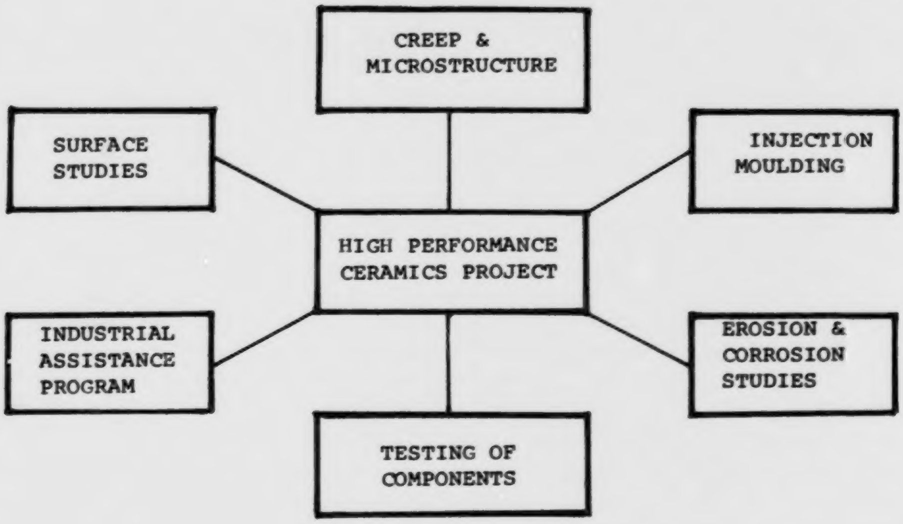

CREEP & MICROSTRUCTURE
SURFACE STUDIES
INJECTION MOULDING
HIGH PERFORMANCE CERAMICS PROJECT
INDUSTRIAL ASSISTANCE PROGRAM
EROSION & CORROSION STUDIES
TESTING OF COMPONENTS

FIGURE 25: Advanced Structural Ceramics Development Program in Sweden.

6.3.3.3 Industrial Activities

ASEA Ceram AB, originally a Division of ASEA AB and now a joint venture between ASEA AB, Volvo AB and KemaNord Industrikemi AB, has been part of the Swedish program since its inception in 1976. It has developed a special hot-isostatic pressing process for the fabrication and manufacture of complex silicon nitride parts for engines. (e.g., as rotors and stators). This technique is claimed to be suitable for mass production of advanced ceramic components of all compositions. Injection molding techniques are used as the preforming method before the HIP process. ASEA Ceram is now actively marketing its technology under licence to interested companies. Norton in the USA has just completed a licencing agreement.

The United Turbine Company, a subsidiary of Volvo, is developing a small gas turbine engine incorporating ceramic components which can be used in existing automobile designs. The engine is a special design called the KTT system. A number of advantages have been claimed for this system:

- High efficiency and performance
- Design suitable for compact vehicles
- Engine is integrated with transmission
- Suitable for early use of ceramics

The first-generation engine, called the KTT MkI, was designed around an all-metallic engine. Ceramic components are being introduced, however, as technological developments are made. The final aim is an engine called the MkII, in which all components in the hot zones will be made of silicon nitride.

Both Volvo and SAAB-SCANIA are working on the development of gas and diesel engines with ceramic components. Details are not yet available.

AB Sandvik Hard Materials is working on cutting tools made of advanced ceramics, particularly silicon nitride and sialon materials. They are already marketing some compositions.

6.3.4 Advanced Ceramics in the United Kingdom

The development of advanced ceramics for engine applications was initiated in the United Kingdom in the early 1960s. Development work was carried out both in industry (Lucas, Rolls Royce) and government laboratories. In the 1970s, two significant developments took place: first, the development of sialon materials at the University of Newcastle-Upon-Tyne; and second, the development of Refel silicon carbide technology at the UK Atomic Energy Authority. In spite of this significant technological breakthrough, interest waned both on the part of industry and government because of the lack of immediate commercial markets to justify the required large financial commitments - R & D as well as manufacturing.

Largely influenced by international developments, particularly in the USA and Japan, both industry and government have now recognized the need for a new national commitment to invest in the development of advanced ceramics. This renewed enthusiasm is based on the realization that the UK cannot afford to lag behind its competitors who are already making significant progress, both in the development and commercialization of advanced ceramics; and that a surge in R & D investment will give industry an opportunity to accelerate progress and leap-frog foreign competition, and so recover its share of world markets and trade.

Industry, for its part, has already taken active steps to make a commitment. Two industrial "clubs" have been formed. The development of gas turbine engines with ceramic components is led by Rolls Royce; the consortium of 10 companies is known as the "Rolls Royce Club". Twelve projects, centred on developing suitable manufacturing processes, understanding the behaviour of ceramics - particularly under stress conditions within the gas turbine engine - and overcoming defects in ceramics, are being supported by the government through the Department of Trade and Industry. The cost of these projects is estimated to be about $9 million in the 1985-88 period.

The second "club", known as the Consortium for Ceramic Applications in Reciprocating Engines (CARE), consists of a group of about 20 companies including car, auto parts and ceramic manufacturers. Its members include: Ford, British Leyland, Morgan Matroc, Lucas, Doulton, Turner-Newall, Smith Industries, Royal Worcester, Associated Engineering Limited, Perkins Engine, and GKN Technology Limited. The club is said to be formulating detailed proposals for submission to the government.

The government, for its part, is considering an overall industry support program, costing about 120 million over a five-year period (with industry providing about half the amount). This budget is for advanced materials in general; the portion for advanced ceramics is not available. In assessing the investment commitment, the government appears to be keenly aware of the opportunities for industry in the long run. Two other considerations are also playing a role: the availability of good scientific and technological capabilities in industry, university and government laboratories; and the long time scale for materials innovation, development, and exploitation, and the resulting high risks when compared with other technologies.

Details of R & D efforts in industry are not available. The British Ceramic Research Association is actively involved in the development of advanced ceramics, with a staff of about 35. BCRA is doing the work on behalf of individual companies on a contract basis. In addition, it has a big program partially supported by the EEC and the UK government.

A number of universities (see Table 22) are actively involved in the development of advanced ceramics - notably Leeds University and the University of Newcastle-Upon-Tyne. With the new interest of industry and government, it is likely that more universities will get support for work in this area.

The UK Atomic Energy Authority at Harwell has concentrated on developing plasma-coating technology. The company is assisting a number of auto parts manufacturers on a contract basis in the development of parts.

A list of automobile, engine and ceramic companies working on advanced ceramics is given in Table 23.

6.3.5 Advanced Ceramics in France

Research on engineering ceramics in France did not begin as early as it did in the UK. The industrial development of these new materials did not proceed as fast as it did in the USA, Japan or West Germany. However, there has been an increasing interest in engineering ceramics in the last 15 years, and considerable R & D activity exists in universities, government laboratories and industry.

The development of engineering ceramics in France has not given rise to such well-defined programs as those that exist in the USA, Japan, and West Germany. This is because government policy supports short-term, result-oriented projects rather than long-term, risk-oriented programs.

A number of universities are actively studying fundamental properties of advanced ceramics and their processing. The financial support comes from various government ministries, such as research, industry, defence, etc. Also, CNRS (the French equivalent of the National Research Council) has its own laboratories where considerable basic research takes place. As well, advanced research is conducted at various universities. The typical duration of the programs appears to be two years.

Industrial companies obtain larger R & D support from govermment agencies, mostly from defence and industry ministries, for mission-oriented programs. University-industry joint programs are also encouraged, particularly in advanced materials and process development areas.

Industrial activities on advanced ceramics are briefly reviewed.

TABLE 22

List of Universities and Government Laboratories Working on Advanced Ceramics in the United Kingdom

Universities

University of Aberdeen
University of Leeds
University of Newcastle-Upon-Tyne
University of Oxford
University of Sheffield
University of Warwick

Government Laboratories

UK Atomic Energy Authority
British Nuclear Fuels Limited
Admiralty Marine Testing Est.
British Ceramics Research
Royal Radar Establishment
National Gas Turbine Est.

TABLE 23

List of Industrial Companies Working on Advanced Ceramics in the United Kingdom

Car & Engine Companies

Leyland Diesel
B. L. Technology
Ford UK
Rolls Royce
GKN Technology Ltd.
Perkins Engine
AE Turbine Components Ltd.

Ceramic Companies

AED (Silicon Nitride) Ltd.
Alcan International
Magnesium Electron
Morgan Matroc
Doulton Industrial Products
Turner-N Wall Materials Ltd.
B. P. Research Ltd.
Royal Worcester
Lucas Cookson
Chloride Silent Power
Plessy
ICI

Alumina Ceramics

Rhone-Poulecnc is the main producer of alumina powders for ceramics. Various grades are produced for refractories as well as technical ceramics. Two smaller companies, Criceram in the Pechiney Group and la Pierre Synthetique-Baikowski, are world leaders in the manufacture of pure alum-derived alumina powders for the production of translucent envelopes of high-pressure sodium vapour lamps.

Sintered alumina ceramics are chiefly produced by three companies: Cice-Isolantite in the Stettner Group, Desmarquest in the Pechiney Group, and Ceraver in the CGE Group. The product range includes wear and friction parts, cutting tools, crucibles, medical prostheses, armour, ceramics for optics and electronic ceramics.

Zirconia Ceramics

Interest in zirconia ceramics appears to be growing significantly in France, probably because of its potential use in diesel engines.

Thann et Mulhouse (in the Rhone-Poulenc Group) and Criceram (in the Pechiney Group) make different grades of zirconia powders for the manufacture of partially stabilized zirconia ceramics as well as special fine powders suitable for ZTC ceramics.

SEPR (in the Saint-Gobain Group) is a world-renowned producer of fused cast refractories for glass-melting furnaces. It is also a major supplier of zirconia grinding media and a future supplier of zirconia for the manufacture of engineering ceramics.

Desmarquest (in the Pechiney Group) is the main French producer of PSZ ceramics as well as zirconia oxygen sensors. Ceratech, (a joint venture between Renault and Norton) manufactures zirconia-mullite ceramics and is positioning itself to supply future Renault requirements of advanced ceramics.

Plasma spraying of coatings based on ZrO_2 and Cr_2O_3 is a technique used in several firms, including: Le-Guellec, SFEC, CEA, Leroy-Somer, Soma Europe Transmission, Turbomenca, SNIAS and SNECMA.

Silicon Carbide

Marcoussis, in the CGE Group, is developing SiC ceramics that are are being commercially produced by Ceratech. The present applications are wear and friction parts, high temperature heat exchangers, fans and atomic energy equipment.

Silicon Nitride and Sialons

Silicon nitride powder suppliers in France are Rhone-Poulenc, ELF and, recently, Criceram.

Silicon nitride and sialons are produced by Desmarquest and Ceratech. Desmarquest has developed low-cost sialon powders as well as SSN and HPSN. Ceratech is working on the production of high-performance ceramics based on Si_3N_4 by pressureless sintering and post-HIPing techniques. Wear components, high temperature structural parts, rolling elements, cutting tools and ball bearings are the prospective applications.

Fibre Composites

In general, the development of ceramic-ceramic composites is carried out by industrial companies for defence applications. SEP and Aerospatiale are well known for high-performance composites. The former works mostly on C-SiC, SiC-SiC, and C-Al_2O_3 systems; the latter on the SiO_2-SiO_2 and SiO_2-SiC systems. The market for these products include weapons, missiles, civilian aircraft and racing cars. Marcel Dassault Co. is also an important producer of high-performance composites for its own production of fighter planes Desmarquest is working on the development of Al_2O_3 long fibres and is already producing ZrO_2 fibres.

Engine Applications

French car makers - the nationalized Renault Group and the private Peugeot-Citroen-Talbot Group - as well as the companies involved in high-power engines (e.g., SEMT in the CGE Group) are working on diesel engines. Gas turbine engines have not aroused much interest. The work is on 'minimum cooled' diesel engines using zirconia as the insulating material.

6.4 Advanced Ceramics in Japan

6.4.1 General

The general development and commercialization of advanced ceramics forms the centrepiece of Japan's industrial strategy. Both industry and government are cooperating in making this strategy work. The interest and commitment of industry is driven by market forces, particularly the need for these materials to support other high-technology industries, and the potentially large market for engine applications. The interest and commitment of government is based on national needs and the belief that advanced ceramics hold the key to many of Japan's energy problems. It also believes that advanced ceramics will play a vital and supportive role in the development of frontier industries (such as the search for petroleum substitutes, the aerospace and space industries, the biotechnology industry and electronics), and that advanced ceramics, by themselves, have the potential to generate whole new industries.

Japan is already a world leader in advanced ceramics, accounting for about half of world production. It dominates the electronic components business, particularly in integrated circuits packaging. It is generally accepted that Japan has won the race for supremacy in the 'functional ceramics' market, and is leading the race for supremacy in the 'engineering ceramics' market.

Japan is widely perceived as having mounted a committed national effort, public as well as private, to dominate the advanced ceramics market internationally. This is demonstrated by the fact that Japan is now estimated to have captured about 50 percent of the present world market in advanced ceramics. Japan has already started to manufacture some ceramic components for diesel engines (30,000 glow plugs per month and 20,000 swirl chambers per month). Companies have started reproducing ceramic turbochargers at the rate of about 1000 per month. The Japanese government, and more important, the banking community seem to have made a commitment to ensure success by funding substantial research and development through purchasing and pricing strategies, and by creating vigorous educational programs to provide the required technical talent.

Japan is already in the forefront of several areas of technology and, therefore, has to develop new technologies to stay ahead of other countries. Both of these considerations have influenced the development of a new national consensus that Japan should change her policies for science and technology from emphasizing 'imitation' to promoting 'invention' and 'creativity'. Success in achieving world leadership in advanced ceramics is a reflection of this new consensus.

6.4.2 Government's Role and Influence

The origin of Japan's commitment to advanced ceramics is a combination of economic necessity and opportunity. Not only are basic industries such as aluminum, steel and refractories being threatened by third-world countries, but even some high-technology industries are under severe economic pressures from countries with relatively cheap labour. Japan anticipates that the development of the advanced ceramic industry will make a major contribution to some of their most important national goals:

- Being a nation poor in natural resources, the use of advanced ceramics would enable Japan to substitute indigeneous materials for imported raw materials, and would also contribute to energy conservation, lowering its dependence on imported petroleum.*

---

* It is projected that by using advanced ceramics Japan can cut its oil consumption by 10 percent, and the cost of gasoline per car can be cut by $240/year. Also, 10 percent savings in cobalt is projected.

- Superiority in advanced electronic ceramics adds another advantage to their already strong electronic industries.

- Becoming the world leader in advanced engineering ceramics will directly result in sizeable new exports of the products themselves and indirectly add to the value of automotive, machine tool and aerospace exports.

Japanese government involvement in ceramics is given in Table 24. Advanced ceramics is being supported by a number of ministries such as the Ministry of Education, in universities; the Science and Technology Agency (an agency directly reporting to the Office of the Prime Minister), in the National Institute for Inorganic Materials; and the Ministry of International Trade and Industry in in-house laboratories and industry.

As a result of favourable and interlocking relationships between the Japanese government and business, it is characteristic that following the formulation of government policies, business accepts government leadership. The government support for specific technological areas exercises considerable leverage on the entire national effort. This is reflected in a comparison of the ratio of research by government in different countries:

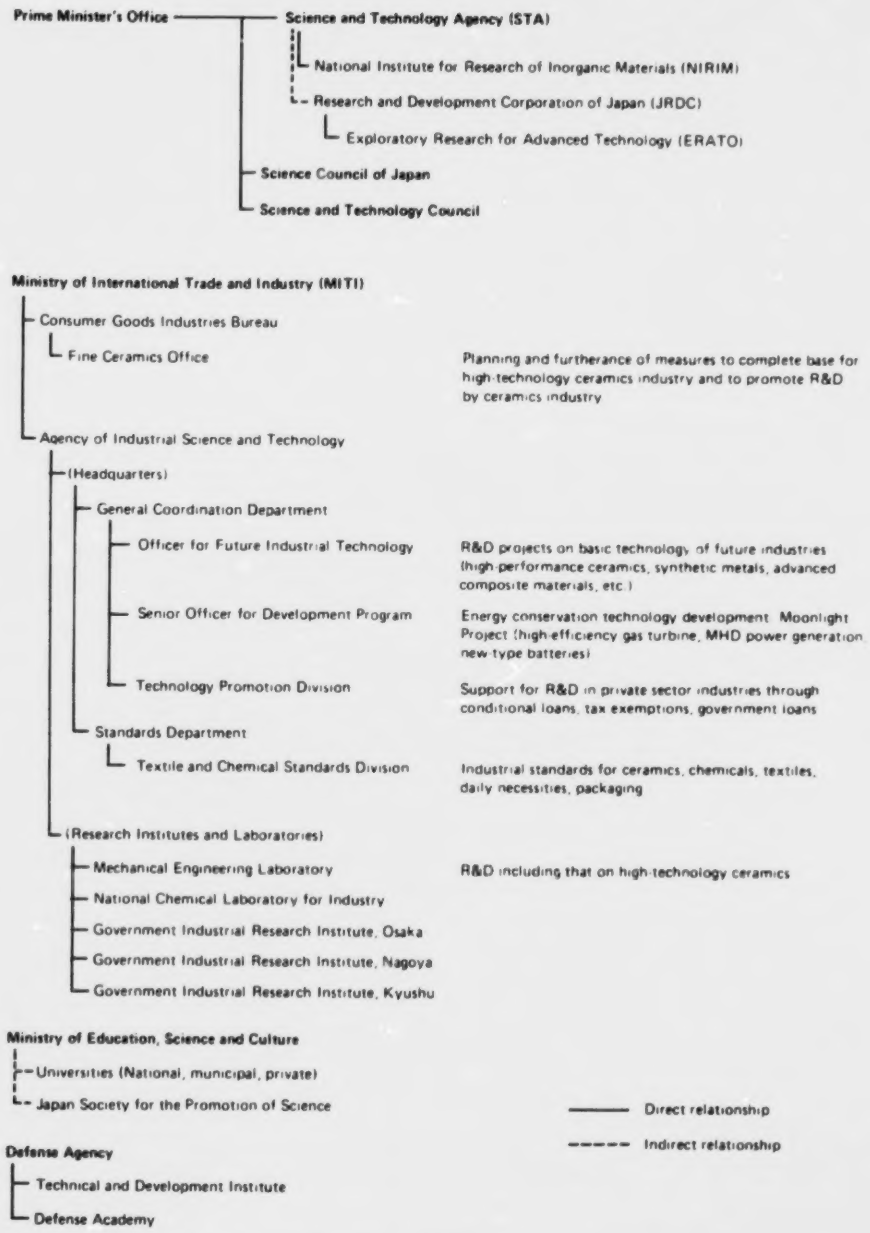
Country	**Year**	**Overall R & D Expenditure (in $ thousands)**	**Ratio 'R' Borne by Government**
Japan	1979	40,636	27.4
USA	1979	118,962	49.3
West Germany	1978	31,851	46.7
France	1979	22,407	58.4
UK	1979	13,130	49.2

(Source: American Ceramics Society)

6.4.3 Government Coordination and Management of Advanced Ceramics Programs - Role of MITI

The advanced ceramics effort in Japan is a product of both government and private industry initiatives. The organizational policies and institutional arrangements that coordinate and manage this effort reflect the close working relationship between the Japanese government and business. They also reflect the capacity of Japanese firms to compete vigorously with each other in a manner that is constructive for the national economy.

TABLE 24



- **Prime Minister's Office**
  - **Science and Technology Agency (STA)**
    - National Institute for Research of Inorganic Materials (NIRIM)
    - Research and Development Corporation of Japan (JRDC)
      - Exploratory Research for Advanced Technology (ERATO)
  - **Science Council of Japan**
  - **Science and Technology Council**
- **Ministry of International Trade and Industry (MITI)**
  - Consumer Goods Industries Bureau
    - Fine Ceramics Office
      Planning and furtherance of measures to complete base for high-technology ceramics industry and to promote R&D by ceramics industry
  - Agency of Industrial Science and Technology
    - (Headquarters)
      - General Coordination Department
        - Officer for Future Industrial Technology
          R&D projects on basic technology of future industries (high-performance ceramics, synthetic metals, advanced composite materials, etc.)
        - Senior Officer for Development Program
          Energy conservation technology development. Moonlight Project (high-efficiency gas turbine, MHD power generation new-type batteries)
        - Technology Promotion Division
          Support for R&D in private sector industries through conditional loans, tax exemptions, government loans
      - Standards Department
        - Textile and Chemical Standards Division
          Industrial standards for ceramics, chemicals, textiles, daily necessities, packaging
    - (Research Institutes and Laboratories)
      - Mechanical Engineering Laboratory
        R&D including that on high-technology ceramics
      - National Chemical Laboratory for Industry
      - Government Industrial Research Institute, Osaka
      - Government Industrial Research Institute, Nagoya
      - Government Industrial Research Institute, Kyushu
- **Ministry of Education, Science and Culture**
  - Universities (National, municipal, private)
  - Japan Society for the Promotion of Science
- **Defense Agency**
  - Technical and Development Institute
  - Defense Academy

——— Direct relationship
- - - - Indirect relationship

Japanese government involvement in ceramics.

The Ministry of International Trade and Industry (MITI) is probably the best known of its kind in the world. It identifies technological fields that should be cultivated in the long-range national interest (a responsibility termed 'vision'), and undertakes to promote and support research and development in these areas to a limited extent. In addition to organizing support programs in in-house laboratories, it supports R & D with industry. This support from government is considered by industry as 'seed money'. Industry invests a large portion of these funds to develop and commercialize the products. It is estimated that the industry/government funding ratio is about 10-20 to 1.

Recently, MITI has opened a 'Fine Ceramics Office' to administer programs and promote the development of advanced ceramics.

To assist and accelerate the growth of advanced ceramic industries, MITI is planning to implement a number of programs, particularly because of the participation of small- and medium-sized companies. The following activities are under consideration:

- Greater standardization and effectiveness in the evaluation of materials;
- Establishing a structure for information exchange;
- Establishing an advanced ceramics experimental centre;
- Preparation of statistics;
- Increasing public awareness and knowledge;
- Re-education of engineers and scientists already in the work force.

Japanese industry agrees with the importance of ceramics that MITI has identified. This is shown in the results of a survey of division directors in 100 important Japanese companies to determine the 10 most significant technological innovations since the 1973 'oil shock'. The high ranking for advanced ceramics (fifth) shows the wide-spread belief in the importance of this field, since it represents the consensus of technical managers in many fields and companies not dominated by ceramic interests.

Ranking of Ten Most Important Technological Innovations Since 1973

Innovation	Number Ranking (Number of Directors Ranking This First)	Rating
1. Large-scale integration applications	86 (67)	397
2. Biotechnology	41 (5)	151
3. Fibre optics	39 (4)	129
4. Industrial robots	35 (7)	104
5. Advanced ceramics	42 (0)	103
6. Interferon	31 (0)	86
7. Office automation	23 (8)	77
8. Other new materials	21 (0)	41
9. Super computer	11 (2)	37
10. Space technology	14 (1)	32

Source: The economic industrial newspaper Nikkei Sangyo Shimbun, August 16, 1983.

In addition to funding of R & D efforts in industry, MITI has taken a number of other initiatives to promote the development of the advanced ceramics industry in Japan and the commercialization of its products. Two of the most important are:

- Promoting the creation of industrial R & D associations
- Promoting public awareness programs

Industrial R & D Associations

To date, MITI has sponsored three industry-oriented associations which are contributing significantly in the development and commercialization of advanced ceramics.

New Ceramics Discussion Group

The group, established in 1972, has 197 industrial members. It is managed by Professor Mitsue Koizumi, Director of the Institute of Scientific and Industrial Research, Osaka University, Osaka. The group holds meetings and seminars on advanced ceramics, and administers a Ministry of Education, Science and Culture project on "New Investigations of Functional Ceramics".

Engineering Research Association for High Performance Ceramics

This association, located in Tokyo, was set up in 1981 to monitor MITI-supported research projects for 15 industrial companies, as well as four government research institutes. The members of this association are listed in Table 25.

TABLE 25:

Members of the Engineering Research Association for High-Performance Ceramics

Member	Assignment
Toshiba Corporation	Sintering of silicon nitride
Kyocera, Ltd.	Optimization of the sintering process
Asahi Glass	Shaping and sintering of silicon carbide ceramics
NGK Spark Plug	Two-step sintering of silicon nitride
NGK Insulators	Development of technical assessment methodology
Showa Denko K.K.	Fabrication of silicon carbide
Denki Kagaku Kogyo K.K.	Fabrication of silicon nitride from silicon powders or silicon halides
Toyota Machine Works	Apparatus for testing bending strength at high temperature
Kobe Steel	Sintering of silicon nitride by hot isostatic processing
Toyota Motors	Measurement of high-temperature strength
Inoue Japax	Machining and fabrication
Sumitomo Electro-Chemical	Minimizing grain size distribution
Kurozaki Refractories	Corrosion tests
Shinagawa Refractories	Thermal fatigue testing
Ishikawajima Harima Heavy Industries	Design of mechanical parts

NOTE: National labs participating in the association are the Government Industrial Research Institute, Nagoya; Mechanical Engineering Laboratory; Government Industrial Research Institute, Oska; and National Institute for Research of Inorganic Materials. The initial term is 10 years (three years for basic research, three years for model development, and four years for production and evaluation). The funding is 13 billion yen (also $57 million).

Japan Fine Ceramics Association

This association was established in July 1982 to promote the participation of industrial companies who were traditionally not in ceramics, as well as to focus on the needs of advanced ceramic industries. The association, located in Tokyo, promotes and coordinates industrial activities in advanced ceramics. The association has a total of 172 company memberships: 158 normal members ($1600/year subscription) and 14 cooperative members ($800/year subscription). The membership, by company type, as of April 1983, is given in Table 26. The role of the association is seen as a venue for the unification and matching of needs of ceramics manufacturers and users through mutual information exchange.

Promotion of Public Awareness Programs

Improving public awareness of the advantages of advanced ceramics and the benefits that can be obtained by their use is an important aspect of Japan's strategy to make advanced ceramics increasingly acceptable to the public, which is already aware of steel, plastics and glass in engineering materials applications. MITI is sponsoring the "Fine Ceramics Fair", held annually in Nagoya. At the 1985 Fair, 147 companies representing all aspects of advanced ceramics - from raw materials to processing, applications and uses - were represented. The fair received good support from the public, particularly because advanced ceramics are being used to manufacture consumer products such as scissors, knives, golf clubs and ice skates.

6.4.4 Review of MITI Programs on Advanced Ceramics

The Agency for Industrial Science & Technology (AIST), one of the three agencies in MITI, is responsible for developing and implementing policies and programs for the development of advanced ceramics. At present, this is being done through the "Fine Ceramics Office".

AIST has implemented three important national programs which are well known today:

- Sunshine Project (initiated in 1974)
- Moonlight Project (initiated in 1978)
- Industrial Base Technology Development Project (initiated in 1981).

The objectives of these programs, in which advanced ceramics are an element, are shown in Figure 26.

TABLE 26

Classification of Company Types in the Japan Fine Ceramics Association

Company Type	Number
Ceramics	41
Chemicals	32
Electrical Appliances	25
Steel & Non-Ferrous Metals	23
Machinery	23
Automobiles	7
Heavy Industry, Engineering	7
Other	14
TOTAL	172

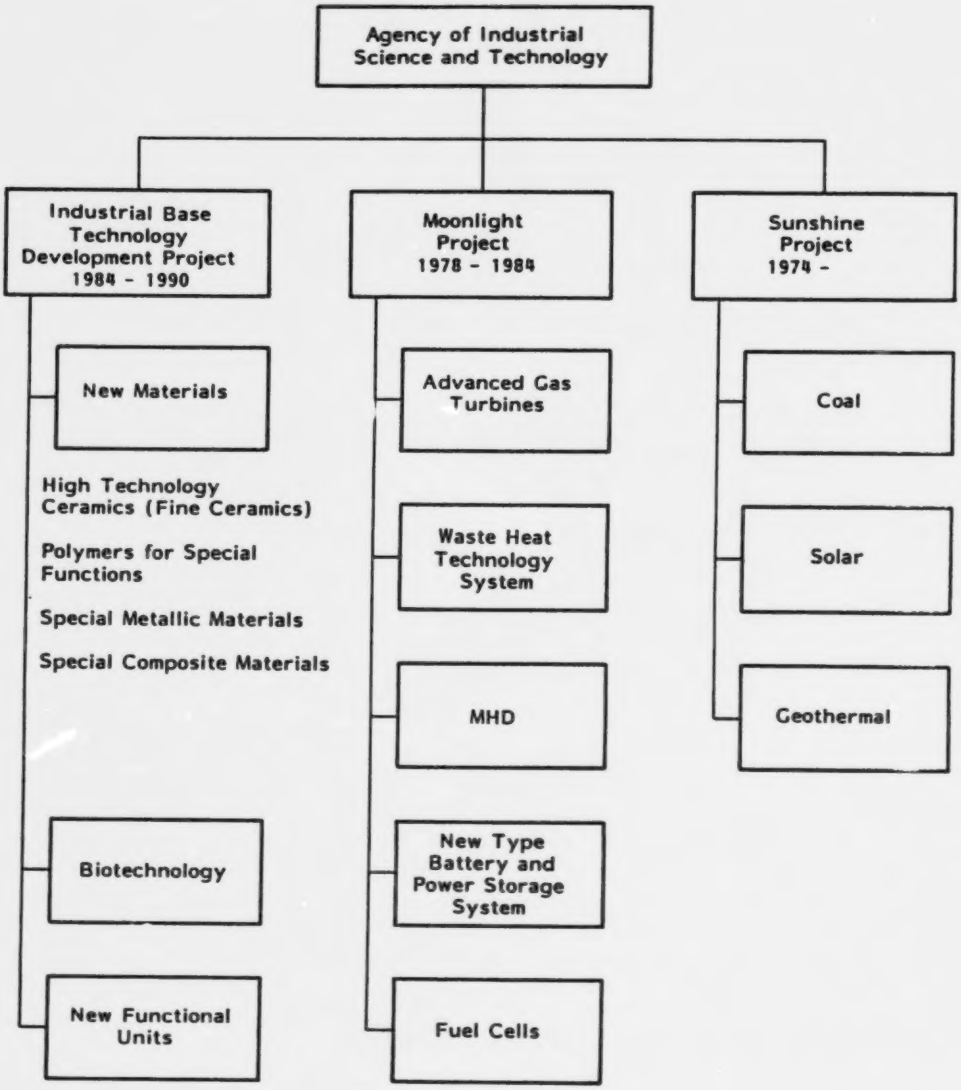

Agency of Industrial Science and Technology
Industrial Base Technology Development Project 1984 - 1990
Moonlight Project 1978 - 1984
Sunshine Project 1974 -
New Materials
High Technology Ceramics (Fine Ceramics)
Polymers for Special Functions
Special Metallic Materials
Special Composite Materials
Biotechnology
New Functional Units
Advanced Gas Turbines
Waste Heat Technology System
MHD
New Type Battery and Power Storage System
Fuel Cells
Coal
Solar
Geothermal

FIGURE 26: Advanced Ceramics Programs in Japan Sponsored by MITI

The Sunshine Project did not have ceramics-related activities directly attached to it. However, it is quite evident that, based on the experience of the project in the early years 1974-1977, the need for high-temperature, high-performance ceramics was recognized. Thus, when the Moonlight Project was initiated in 1978, specific projects related to the development of ceramic components were incorporated.

Whereas the Sunshine Project was aimed at developing new and alternative sources of energy to replace oil, the Moonlight Project was designed to develop energy conservation technologies. As shown in Figure 26, five areas were chosen:

- Advanced Gas Turbines
- Waste Heat Utilization Technology
- Magneto-hydrodynamics Generation
- New-Type Battery and Power Storage Systems
- Fuel Cells

The ceramic activities of the overall Moonlight Project are estimated to be about $1 million per year, ($7 million over the seven-year project.

In the advanced gas turbine program, ceramic turbine blades and combustors were developed. The actual testing of the components was carried out by the Advanced Gas Turbine Engineering Research Association (AGTERA), a conglomerate of private industry and government laboratories. In addition to government laboratories, the association has the following industrial members: Mitsubishi, Toshiba, Kawasaki, Hitachi and Ishikawajima.

The 10-year Industrial Base Technology Development Project, (initiated in 1981), has three broad themes: new materials, biotechnology and new functional units. In the area of new materials, four categories have been selected for development, advanced ceramics being one of them. The advanced ceramics project is being coordinated through the Engineeering Research Association for High Performance Materials. The performance objectives for the ceramic materials are listed in Table 27. The timeframe for accomplishing the major tasks is given in Figure 27.

6.4.5 Industrial Activity in Advanced Ceramics

The Japanese ceramic industry is now very well established, both in the scope of manufactured products and in the technological capabilities for further developing advanced ceramic products. These include engineering ceramic components (engine components, wear-resistant parts) and functional ceramics (electrical and electronic components, sensors, and bioceramics).

TABLE 27

Performance Objectives of MITI High-Technology Ceramics Program

Classification	Objective	Values
High-strength materials	≥ 1200°C in air after 1000 hours holding:	
	Weibull modulus	$M \geq 20$
	Average tensile strength	$\bar{\sigma} \geq 30$ kg/mm^2
	1200°C in air after 1000 hours continuous loading:	
	Creep rupture strength	$\bar{\sigma} \geq 10$ kg/mm^2
Corrosion-resistant materials	≥ 1300°C in air after 1000 hours holding:	
	Weibull modulus	$M \geq 20$
	Corrosion resistance (weight gain)	≤ 1 mg/cm^2
	Average tensile strength	$\bar{\sigma} \geq 20$ kg/mm^2
Wear-resistant materials	Room-temperature	
	Wear resistance	$\leq 10^{-4}$ mm^3/kg·mm
	Surface flatness	$R \leq 2$ μm
	800°C in air after 1000 hours holding:	
	Weibull modulus	$M \geq 22$
	Average tensile strength	$\bar{\sigma} \geq 50$ kg/mm^2

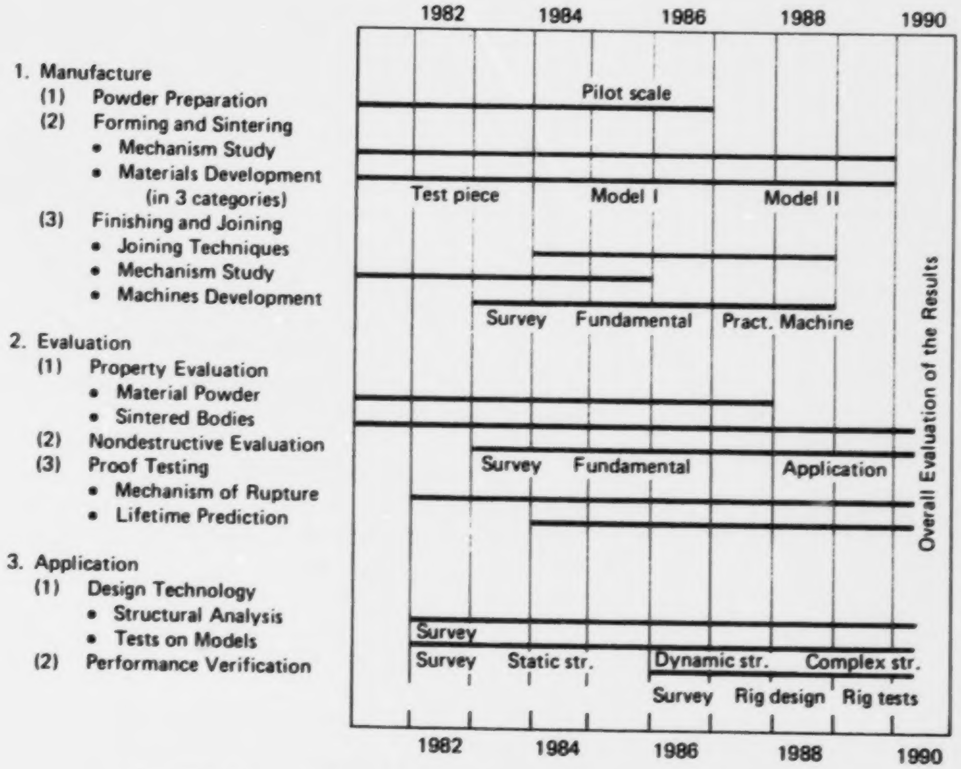


FIGURE 27: Schedule of MITI Development Program

The relative size of the ceramic industry in Japan is given in Table 28. There are 33,323 companies in all, employing 530,466 employees. From this, it is clear that the ceramic industry in Japan is a very important part of the economic picture. However, the number of companies from this group participating in advanced ceramic activities is very small. It is quite likely, however, that as the diffusion of technology takes place, the number will increase. The number of research workers employed by the ceramic industry, compared with other industry sectors, is given in Table 29. In 1981, the number was 4,799. The number at present is significantly greater; one estimate indicates that 2000 scientists are working in advanced ceramics alone.

Because of the realization that there is a good market potential for advanced ceramics in the medium and long term, a wide range of companies have entered, or are planning to enter, this field. Participation of these companies will be in the form of ceramics manufacturers, of equipment (or engineering), or a combination of these. There are already some 120 companies which sell some type of new ceramics product; about 40 suppliers of raw materials and 50 manufacturers of equipment for manufacturing and processing new ceramics. About 60 companies engaged in advanced ceramics are listed on the stock exchanges; two-thirds of them entered this field from the materials industry; one-third started out in the processing and assembly industry. Some of the important Japanese firms active in the development of advanced ceramics and commercialization are listed in Table 30.

Three basic motives are influencing companies to enter the advanced ceramics market:

- Diversification by materials manfacturers to apply existing technology to achieve higher added-value and create more profitable products;
- Upgrading of an existing technology (this applies to existing ceramic manufacturers);
- Participation by processing and assembly industries, in which the users of materials are led by necessity to develop new materials on their own.

TABLE 28

Relative Size of the Ceramics Industry in Japan

Industries	(a) Number of companies	(b) Number of employees	(b)/(a)	(c) Value of shipments
All industries				$\$ \times 10^{9\dagger}$
1–9 persons	563 803	2 159 056	3.8	58
10–29 persons	121 298	2 062 144	17.0	103
30–99 persons	40 417	2 103 728	52.1	140
100–999 persons	13 146	3 085 015	234.7	328
1000 or more	640	1 449 919	2265.5	207
Total	739 304	10 859 862	14.7	836
Mfgs. of Ceramics: Stone, Clay, Glass Products				
1–9 persons	22 069	90 695	4.1	2.5
10–29 persons	7 704	137 022	17.8	8.9
30–99 persons	2 902	145 534	50.1	8.3
100–999 persons	632	135 541	214.5	11.3
1000 or more	16	21 674	1354.6	2.0
Total	33 323	530 466	15.9	33.0

*Source: Census of Manufacturers, 1979, MITI. †Assumes 220 yen=$1.00.

TABLE 29

Number of Researchers by Line of Business in Japan

	Researchers (persons)				
	1977	1978	1979	1980	1981
All industries	151 437	153 706	157 279	173 244	184 889
Manufacturing Industries	141 839	144 018	148 250	163 867	175 088
Textile	2 245	1 725	2 080	3 846	2 371
Pulp and paper	1 235	1 254	1 448	1 355	1 527
Chemical	28 259	29 228	29 506	31 556	32 847
Oil/coal products	1 101	1 273	1 274	1 316	2 363
Rubber products	2 230	2 598	2 830	3 180	3 423
Ceramics	4 004	3 894	3 652	5 355	4 799
Iron and steel	4 124	4 176	4 305	4 434	4 800
Nonferrous metal	2 130	2 186	2 403	2 385	2 895
Machinery	13 426	14 375	12 642	15 273	15 390
Electrical Machinery	49 465	47 939	51 174	55 467	58 873
Transport Machinery	13 705	13 855	15 132	16 169	17 682
Precision Machinery	4 590	4 935	5 685	6 188	7 061

* Sources: Reports on the Survey of R&D for 1973 through 1980 and Outline of the Survey of R&D for 1981.

TABLE 30

Japanese Companies Active in Commercialization of Advanced Ceramics

Chemical/Metallurgical Firm (Powders)	**Advanced Ceramics Components/Parts Firms**	**End Products Firms Incorporating Advanced Ceramics**
Showa Denko	TDK Electronic	Hitachi Ltd.
Mitsubishi Chemical	Kyocera International	Matsushita Electric
Sumitamo Chemical	Murata	Toshiba Corp.
Ube Industries, Ltd.	Taiyo Yuden	Nippon Electric Co.
Nippon Soda Company Ltd.	Toshiba Ceramics	Fujitsu Limited
Mitsubishi Mining & Cement	Hitachi Metals	Mitsubishi Electric Corp.
Fuji Titanium	NGK-Sparkplug	Sumitamo Electric Corp.
Toray Industries, Ltd.	NKG Insulator	Fuji Electric
Nippon Steel	Asahi Glass Co. Ltd.	
Nippon Carbon	Narumi China	
	Fuji Electrochemical	
	Nippon Tungsten	
	Sumitamo Specialty Metals	
	Tohoku Metal Industries	

Electronic Components	Cutting Tools & Wear Parts	Automotive Engines and Parts
Kyocera International	Nippon Tokushu Togyo	Kyocera International
Nappon Tokushu Togyo	Nippon Tungsten	Nippon Tokushi Togyo
Narumi China	Kyocera International	Nippon Denso
Nippon Gaishi	Sumitamo Electric Ind.	Nippon Shobubia
Tokoyo Denki Kagaxu	Mitsubiskh Metal	Kagoku Koyyo
Taiyo Yuden	Fujikin	Nippon Gaishi
Murata Manufacturing	Nippon Gasishi	
Tohoku Kinzoku Kogyo	Hitachi Chemical	
Unizon		
Matsushita Electrical Ind.		
Nippon Denso		
Nippon Kagaku Togyo		
Fuji Denki		
Chichibu Cement		
Sumitamo Electric Ind.		
Toray Industries, Inc.		

Source: Industry Analysis Division, US Department of Commerce, based on listings in the Ministry of International Trade and Industry (MITI) Handbook 1981-1982.

The motives for various sectors of industry to enter the advanced ceramic field are summarized in Table 31.

6.4.6 University Participation in the Development of Advanced Ceramics

Universities participate in the development of advanced ceramics in two ways: first, in the education of ceramic engineers and scientists to supply the needs of industry, government and universities themselves; and second, by actively participating in research and development on advanced ceramics, with support from government and industry, to meet national objectives.

The number of students in higher education, and the number of degree holders (masters and doctorates) in Japan are compared with those of the USA, UK, West Germany and France in Table 32. It can be seen that Japan rivals the USA in the ratio of students enrolled in higher education (37 percent in Japan and 45 percent in the USA). This far exceeds European countries. Of particular interest is the emphasis on engineering education.

The list of universities where active research on advanced ceramics is being carried out is given in Table 33.

TABLE 31

Motives for Entering the Fine Ceramics Industry

Industry	Motive for entering the fine ceramics industry	Technological connection	Comparison with existing business or reasoning behind the decision to enter the field of fine ceramics	Future direction (example)
Ceramics	Upgrading of the main line of business	Calcination technology, pulverization technology	Higher added value for the main line of business	Systemization and more advanced functions
Chemicals, textiles	Diversification, advancing down-market	A part of inorganic chemistry (the utilization of inorganic compounds for fine ceramics)	It is relatively easy for this industry to enter the field of fine ceramics because it has long been involved in a fine market (fine chemicals)	Advancing down-market by producing finer raw materials
Steel and nonferrous metals	For the industry's own consumption, diversification	An accumulation of technology as a producer and as a user in refractory materials and cutting materials	It is thought that the existing material (steel) will never be completely replaced	Activity of subsidiaries
Electric industry	Pursuit of high-function materials, (going up-market), (for the industry's own consumption)	User of fine ceramics as electronic materials; ability to evaluate materials, judgment and precision processing technology as a user	With no up-market knowledge (of materials), development of the downstream market (existing business) is impossible; materials suited to purposes of use are needed	Manufacturing for the industry's own use, joint research and development with materials manufacturers
Machinery	Improvement of systems by introducing new materials	The Knack for selecting more suitable parts and materials	The upgrading of sensor functions is essential	Development of various kinds of sensor materials
Automobiles	Energy saving, introduction of parts	Research since long ago in the evaluation and use of ceramics as catalysts and (energy-saving) engine materials	Research and development are essential for lighter weight, better engine efficiency, and the realization of new sources of motive power	Joint development with materials manufacturers, the development of new concepts based on new materials
Heavy industry and engineering	New products and improved systems through the introduction of new materials	The knowhow to design materials	Business opportunities are expanded by branching out into related business fields	Toward a general system industry involving fine ceramics (dealing with related businesses)

(Source: The Long-Term Credit Bank of Japan, Ltd.)

TABLE 32

Number of Higher Education Students and Holders of Academic Degrees in Japan, USA, UK, France and West Germany

Number of Higher Education Students and Holders of
Academic Degrees in Japan, USA, UK, France and West Germany

Country	FY	Total	Cultural and Social Sciences	Physical Science (%)	Engineering (%)	Agri-culture	Medical Science	Others
Japan	1970	1 619 649	857 139	42 265 (2.6)	320 029 (19.8)	53 356	72 284	274 576
	1981	2 110 513	1 108 688	55 212 (2.6)	368 770 (17.5)	63 195	129 888	384 760
United States	1970				231 700			
	1975	8 727 826			231 400 (2.7)			
	1981	9 403 049			387 600 (4.1)			
Britain	1970	185 872	81 167	45 775 (24.6)	30 261 (16.3)	3 640	20 616	4 413
	1979	245 093	113 157	55 590 (22.7)	35 817 (14.6)	5 124	27 629	7 726
France	1970	572 614	346 689		89 455 (15.6)		112 275	24 195
	1978	720 335	389 195		103 776 (14.4)		161 931	65 433
West Germany	1970	407 107	164 514	69 917 (17.2)	39 580 (9.7)	7 065	44 748	85 283
	1979	970 284	455 433	141 653 (14.6)	176 494 (18.2)	24 014	83 238	89 422

* Comparable data not available or not collected.

Source: Keiichi Shima, "Science and Technology in Japan, in Journal of Japanese Trade and Industry, No. 5, pp. 21-22, 1983.

Number of Higher Education Students and Holders of
Academic Degrees in Japan, USA, UK, France and West Germany

Country	FY	Total	Cultural and Social Sciences	Physical Science (%)	Engineering (%)	Agri-culture	Medical Science	Others
Japan	1970	13 879	2 847	1 794 (12.9)	4 633 (33.3)	1 026	3 219	360
	1981	21 665	4 124	2 532 (11.7)	8 161 (37.7)	1 695	4 234	919
United States	1970	262 616	102 056	26 520 (10.1)	21 797 (8.3)	3 543	6 215	102 485
	1978	333 809	141 349	22 692 (6.8)	21 292 (6.4)	4 944	16 203	127 329
Britain	1970	12 901	4 183	4 017 (31.1)	2 727 (21.1)	320	835	819
	1978	18 080	6 322	4 374 (24.2)	3 090 (17.1)	501	1 206	2 587
France	1970	7 526	1 702		3 049 (40.5)		2 775	
	1977	17 273	2 421		5 178 (30.0)		9 674	
West Germany	1970	9 728	2 158	1 995 (20.5)	768 (7.9)	332	4 475	
	1979	11 033	2 279	2 467 (22.4)	982 (8.9)	469	4 827	

* Comparable data not available or not collected.

Source: Keiichi Shima, "Science and Technology in Japan, in Journal of Japanese Trade and Industry, No. 5, pp. 21-22, 1983.

TABLE 33

Major Japanese Universities with Ongoing Research Programs in Ceramics

University	Area of R & D
Hokkidao University	Ceramic Powders
Keio University	Ceramic Powders
Kyoto University	Glass, Properties
Kyoto Institute of Technology	Mechanical Properties
Kyushu University	Powders, Solid Electrolytes
Mie University	Glass
Meijyo University	Ultrafine Powders
Nagoya University	Nitrides, Electronic Material
Nagoya Institute of Technology	Solid Electrodes
National Defense Academy	Electronics Materials
Osaka University	Engineering Ceramics
Siekei University	Ceramic Powders
Sizuoka University	Gas Sensors
Tohoku University	Sintering, Fracture Properties
Tokyo Institute of Technology	Advanced Ceramics
University of Tokyo	Electronic Ceramics
Yamanashi University	Crystal Growth

7. CANADIAN PERSPECTIVE

7.1 General

Most of the evidence accumulated in this study on advanced ceramic materials, leads to four important conclusions that will affect and influence the economic and social well-being of Canada. First, advanced ceramics offer an opportunity for the growth and diversification of existing industry - ceramic as well as other sectors - and the potential for the creation of new industries. Second, they hold the key to finding long-term solutions to energy and resource problems, particularly for Canadian resource-based industries, whose products will be threatened or adversely affected by materials substitutions. Third, they are expected to play a vital supportive role in the development and growth of high-technology industries such as electronics, computers, communication, aerospace, robotics and biotechnology. Fourth, they are expected to contribute significantly in improving the productivity of a number of manufacturing industries.

The real question facing Canada today is one of direction and commitment. The question is not whether Canada should invest in the development of an advanced ceramics industry base. The question really is whether Canada can afford **not** to invest in the development and growth of an advanced ceramics industry base. There is only one answer to the question - Canada cannot afford not to invest.

Several countries have a lead over Canada in the development of advanced ceramics and, more important, have a larger industrial base, both in production and consumption, scientific and technical manpower, and educational infrastructure. So Canada must identify niches to take advantage of Canadian strengths such as cheaper energy costs, availability of raw materials and access to the large US market.

7.2 Profile of the Canadian Ceramic Industry

7.2.1 Profile of Traditional Ceramic Industry

Compared with other industrialized countries particularly the United States and Japan, the Canadian ceramic industry is small. Most companies are involved in the manufacture of traditional ceramic products. The products manufactured by these companies can be grouped into different categories as follows:

- Abrasives Plants
- Brick & Tile Plants
- Clay Sewer Pipe Plants
- Glass Plants
- Porcelain Enamel Plants
- Pottery & Whiteware
- Refractories

According to the Operator's List 6 (last published by the Department of Energy, Mines and Resources in 1975), there were 185 manufacturing plants altogether. This increased to about 230 in 1978, the latest year for which information is available. The total number of companies is smaller than this because some of the companies have several manufacturing plants distributed throughout Canada.

The majority of the companies are in the brick and tile and pottery business. There are two big flat-glass manufacturers: Ford Glass Ltd., and PPG (Canada). The former manufactures the glass in Toronto and the latter in Owen Sound. There are also two big container glass manufacturers in Canada: Domglas and Consumers Glass. Both of these are Canadian companies and have a number of manufacturing plants distributed throughout Canada. Fiberglas Canada is a subsidiary of Owens-Corning Fiberglass Corporation in the USA. It has a number of manufacturing plants in Canada and is the major supplier of fiberglass insulations.

Although silicon carbide is made in Canada by a number of manufacturers, it is shipped to the USA raw and processed there. All major refractory manufacturers are subsidiaries of US corporations.

7.3 Profile of the Canadian Advanced Ceramic Industry

7.3.1 General

Because of the diverse applications of advanced ceramics, encompassing a large number of industry sectors, it is difficult to identify the total extent of their penetration in the market place. Because some of these materials and products are so new, specific data categories - separate from other materials or end use products - have not yet been designed to reflect their contribution to the overall industrial data base. Both in the USA and Japan these issues are being addressed, and it is likely that better procedures will soon be adopted for statistical data collection procedures, to reflect the impact of advanced ceramics in the market place. It will be necessary to adopt such procedures in Canada as well.

Primary manufacturers of advanced ceramic products and the suppliers of raw materials (ceramic powders) can be easily identified. It is rather difficult, however, to identify all the users. Advanced ceramics are used in two different ways: first, as finished components in machinery and industrial equipment (e.g., engine components, cutting tools, wear parts); and second, as secondary products to manufacture other components or systems (e.g., as substrates for electronic components, thick and thin film materials for the manufacture of active and passive components on the substrates, detectors, sensors, etc.). In all applications, the original advanced ceramic component is further processed to obtain the desired end result and becomes part of a system for end-use application.

The number of primary manufacturers of advanced ceramics in Canada is very small. It is believed that the number of secondary manufacturers (i.e., those who use advanced ceramics as the source for a finished product) is rather large. All known primary Canadian manufacturers of advanced ceramics have been identified in this study. The data for secondary manufacturers is incomplete, largely because data on multinational companies and imports were unavailable.

7.3.2 Manufacturers of Ceramic Powders for Advanced Ceramics

A list of manufacturers of ceramic powders for the advanced ceramics industry is given in Table 34. At present, there are only four manufacturers: Alcan, Northern Pigment Co., Cominco and Kennametal. Alcan has been a manufacturer and supplier of alumina powders to the ceramic industry for several decades, supplying the Canadian and US markets. Northern Pigment Co., located in Toronto, is a major supplier of specialized iron oxides for the manufacture of ferrites (both soft and hard), which are ceramic magnets. Since there is no demand within Canada, the products are exported, mainly to the USA. Cominco is a supplier of semiconductor materials, of which gallium arsenide (GaAs) - now being used as a substrate in electronics - is an important one. Kennametal Marco Division manufacturers tungsten carbide powder.

A number of silicon carbide grain manufacturers in Canada are also listed in this table. These companies have been in Canada for many years. To date, the raw silicon carbide is shipped to the USA, where it is beneficiated for manufacturing products such as abrasives, heating elements and refractories. At present, the Carborundum Company, in Niagara Falls, NY, is beneficiating the raw Canadian silicon carbide and using it to develop and manufacture engineering ceramic components for engines and other applications. Norton also is using Canadian-made silicon carbide for this purpose. No other companies are involved in the development of engineering ceramics.

Since, at present, the ceramic components for engines and other high-performance applications are only in the developmental stage, the market is relatively small. If, however, the products are accepted in the market place in the coming years, the demand will increase. It is possible that beneficiation will be done in Canada for two reasons: first, cheap electric power, and second, the possible advantage integrating the manufacturing and beneficiation processes in the same facility. It is too early to predict future trends, but with a better integration of North American markets and suitable government incentives, this is probable.

TABLE 34

Manufacturers of Ceramic Powders for Advanced Ceramics

Name of the Company	Products
Alcan Aluminum Limited Montreal, Quebec	Alumina powders
*Electro Refractories and Abrasives Canada Ltd., 60, Notre Dame Street Cap-de-la-Madeleine, Quebec G8T 4B7	Silicon carbide
*The Exolon Company of Canada Ltd., P.O. Box 280 Thorold, Ontario L2V 3Y9	Silicon carbide
*General Abrasive (Canada) Ltd., 3807 Stanley Avenue Niagara Falls, Ontario	Silicon carbide
*Norton Company of Canada, Limited P.O. Box 37 190, rue de Grandmont Quebec, G8T 7W1	Silicon carbide
*Norton Company of Canada, Limited 8001 Daly Street Niagara Falls, Ontario L2G 6S2	Silicon carbide
Northern Pigment Co., Toronto, Ontario	Iron oxide for hard and soft ferrites
*Sohio Electrominerals Montreal, Quebec	Silicon carbide
Kennametal Marco Div. Vancouver, BC	Tungsten carbide
Cominco Trail, BC	Gallium arsenide

* At present these companies manufacture raw silicon carbide in Canada and beneficiate in the USA.

7.3.3 Manufacturers of Electronic Ceramics and Components

The manufacturers of electronic ceramics and components are listed in Table 35. It can be seen that there are few companies and few types of materials manufactured.

Three companies have concentrated in the manufacture of piezoelectric ceramics: Almax Industries (1980) Ltd., of Lindsay, Ontario; Lakeside Electronics Ltd., of Whitby, Ontario, and BM Hi-Tech Inc., of Collingwood, Ontario. Of these, Almax is the oldest and largest with about 60 people. Most of its products are exported to US markets. In addition to piezoelectric ceramics, Almax has diversified into ionic conductors for sodium-sulfur battery and sodium thermoelectric generator applications. More recently, the company has licenced technology from France for the manufacture of high-temperature furnaces, and sialon technology from Lucas-Cookson.

Lakeside Electronics, operating since 1969, is the second-largest manufacturer of piezoelectric ceramics, with about 10 full-time staff. It also manufactures thick-film conducting inks used in making hybrid circuitry. About 60 percent of its products are marketed in the US and about 40 percent in Canada.

BM Hi-Tech Inc. is a relatively new company. It began in 1983 as a Division of Blue Mountain Pottery in Collingwood, Ontario. It has a staff of five and is manufacturing specialized piezoelectric materials as well as sensors and transducers.

Murata Erie North America Limited, in Trenton, is the largest electronic ceramic component manufacturer in Canada, with a staff of about 900, as well as a full product range. It has a central quality control centre in Toronto, to service all North American operations. It is a wholly owned division of Murata in Japan.

IBM Canada Limited of Bromont, has started a facility with a staff of about 1400. This facility manufactures alumina substrates and multilayer integrated circuits. All of their production is to meet IBM product lines.

Magna International, a multi-million-dollar Canadian company in the auto parts business, has started a joint venture company called Powerplex Technology Inc., with Brown Boveri of Germany. They plan to manufacture high-energy-density sodium-sulfur batteries for automotive and other applications. The -alumina battery separator technology is well established at Brown Boveri in Germany and will play an important role in Canadian operations. At present, the company has 13 staff members in related activities. The number is expected to increase to meet the firm's goals.

Neosid (Canada) Limited, a wholly owned subsidiary of a UK company, manufactures soft ferrite components which are used in car radios and TV sets. The company imports the ceramic powders from the UK and fabricates and sinters the components in the Toronto facility. The company has a staff of about 30. It is the only ferrite manufacturer in Canada.

Northern Telecom and Canstar Communications are in fibre optics manufacturing, which is important in the communication business. Northern Telecom has been manufacturing optical fibres at its plant in Saskatoon, Saskatchewan, and using them in their system applications. Canstar Communications (a subsidiary of Canada Wire and Cable), located in Winnipeg, manufacturers fibre optic cables from imported optical fibres. It is supplying the cables to the transcontinental communication network being implemented by CNCP.

A number of companies (between 25 and 50) manufacture hybrid electronic circuits, starting from ceramic substrates and thick-film pastes, to produce resistors, capacitors, dielectric crossovers, etc. Almost all electronic companies in the telecommunications business are involved in this technology. Two groups of companies can be identified: custom hybrid circuit manufacturers and companies which manufacture for their in-house product lines. Epitek Electronics and Circocraft are typical examples of the former group. Epitek is located in Kanata, Ontario, and has a staff of about 100. It manufactures custom hybrid circuits for companies that do not have this facility but need the products for integration with their product lines. Circocraft of Montreal is a relatively new company with similar activities.

A large number of companies manufacture in-house the necessary hybrid and multilayer circuits starting from alumina substrates and using thick-or thin-film technology for incorporating conducting active and passive components. Some of the important companies that are in this category are Litton Systems Canada Ltd., Northern Telecom, Garrett Manufacturing Ltd., Mitel Corporation, Canadian Marconi, CAE Electronics and Microtel.

TABLE 35

Companies Manufacturing Electronic Ceramics and Components

Company	Number of Employees	Products
Almax Industries (1980) Ltd. 61 Needham Street Lindsay, Ontario, K9V 4Z7	60	Piezoelectric Ceramics Ionic Conductors Battery Separators
BM Hi-Tech Inc. Mountain Road Collingwood, Ontario	4-5	Piezoelectric Ceramics Sensors, Transducers
Canstar Communications Winnipeg, Manitoba	N/A	Fibre Optic Cables
Circocraft Montreal, Quebec	N/A	Hybrid Circuits
Epitek Electronics 100 Schneider Road Kanata, Ontario	100	Custom Hybrid Circuits
IBM Canada Ltd. Bromont, Quebec	1400	Alumina Substrates Multilayer Ceramic Components
Lakeside Electronics Ltd. 473 Hensall Circle Whitby, Ontario, L1N 1B9	10	Piezoelectric Ceramics Thick-Film Pastes
Litton Systems Canada Ltd. 312 Rexdale Blvd. Toronto, Ontario	N/A	Custom Ceramic Components for in-house use
Magna International Inc. 257 Wildcat Road Downsview, Ontario, M3J 2S3	13-17	Sodium-Sulfur Battery Alumina Separators (also a big auto parts manufacturer)
Murata Erie North America Ltd. 6338 Viscount Road Mississauga, Ontario, L4V 1H3 (Plant: Trenton, Ontario)	800	Wide Variety of Electronic Ceramic Components

TABLE 35 (cont'd)

Companies Manufacturing Electronic Ceramics and Components

Company	Number of Employees	Products
Neosid (Canada) Limited 10 Vansco Avenue Toronto, Ontario, M8Z 5Z4	30	Soft Ferrite Magnetic Components for Auto Radios and TV
Northern Telecom Saskatoon, Saskatchewan	N/A	Optical Fibres for Communication Applications
Phillips Cables Ltd. Brockville, Ontario	N/A	Fibre Optic Cables
Pirelli Cables Inc. Surrey, BC	N/A	Fibre Optic Cables

7.3.4 Manufacturers of Advanced Structural and Industrial Ceramics

Companies manufacturing advanced structural and industrial ceramics are listed in Table 36. Six of the companies manufacture some type of advanced or industrial ceramics, and at least eight companies are involved in advanced ceramic coatings using plasma technology either for in-house applications or to meet the needs of industrial customers.

EYC Ceramics is a relatively new company located in Espanola, Ontario, and serves the needs of the mining and pulp & paper industries. It has a staff of seven and is manufacturing alumina-based ceramic components. It is also developing zirconia-based ceramics. In addition to the ceramics manufactured in-house, the company also imports components from the USA that it is unable to manufacture in-house, for lack of technology and know-how. The company is aggressively looking at expanding its technological resources so it can serve the needs of industry in northern Ontario. However, it will need assistance for technological development, market development and market penetration.

Electrofuel Manufacturing Company is also a relatively new company located in Toronto. It has a staff of 10 to 12. In addition to the development of lithium batteries, it has developed the manufacturing capability for advanced ceramics. At present, it has developed the technology for the manufacture of boron nitride ceramics and is aggressively marketing it. The company's strengths are advanced fibre processing technology activities (including other advanced ceramic materials, particularly silicon nitride based materials). Being a new company, it is seeking assistance in technological development, market development and market penetration.

Hamilton Porcelains Limited, of Brantford, Ontario, is a well-established company that has been manufacturing industrial ceramics for almost three decades. At present, it has a staff complement of about 120, and manufactures ceramic products based on aluminosilicates, cordierite and zircon. The company is technologically very strong and has introduced a number of new products over the years. It is well known for its infra-red burner products. As part of a commitment to enter the advanced ceramic market more fully, the company has embarked on the development of ionic conductors for fuel cell and other applications. Most of the products are exported to the USA, Europe and Japan.

Home Technics Limited, of Peterborough, Ontario, has a staff of about 20. It has specialized in the manufacture of high-density alumina products - much of it exported to the USA, where it has received market acceptance for specialized applications. It is developing zirconia ceramics to complement its product lines. It is a company with strong technological capabilities and should be able to participate more fully in the development of an advanced ceramic industry base in Canada. However, it will need support both in the development of new technologies and in market development and market penetration.

Industrial Ceramics Limited, of Cookesville, Ontario, has a staff of about 10-15, and manufactures alumina and zirconium silicate products. Most of its products are exported.

Polyceram is located in Montreal and manufactures specialized advanced ceramic products based on ceramic oxides. Its strength is a specialized slip-casting process which can be used in the manufacture of a number of specialized products. Because of its unique technological strength, it should be able to participate in the development of advanced ceramic industries based in Canada. Because it is a small company, it has to be assumed that it will need support and assistance in technological development, market development and market penetration.

All the companies listed above are in the business of manufacturing monolithic ceramic components. Another technology, which is expected to have more widespread use is the technology of using advanced ceramics as coatings on metals. Many coating technologies are available, but the most useful is the plasma technology. Because of the brittle nature of ceramics, coatings are preferable to monolithic ceramics for some applications, particularly where metals have been in use and accepted for mechanical properties. Metco is one of the major companies which supplies plasma equipment, as well as advanced ceramic materials and coating technology. There are about 30 Metco plasma coating units in Canada. Some of the important users are listed in Table 36.

Rolls-Royce and Pratt & Whitney, being aircraft engine manufacturers, use plasma technology for coating metal components. Air Canada and CP Air have plasma facilities to service and maintain aircraft jet engines. George A. Wright & Sons, Peacock Inc. and Vacaro are custom coating companies to service aircraft and machinery industries.

TABLE 36

Companies Manufacturing Advanced Structural and Industrial Ceramics

Company	Number of Employees	Products
EYC Ceramics Box 250 Espanola, Ontario, POP 1CO	7	Alumina and Zirconia Ceramics
Electrofuel Manufacturing Co. 9 Hanna Avenue Toronto, Ontario	10	Boron Nitride Ceramics Battery Separators
Hamilton Porcelains Limited 25 Campbell Street Brantford, Ontario, N3T 5I9	100-120	Mullite, Cordierite and Zirconium Silicate Ceramics, Ionic Conductors
Home Technics Limited 625-646, Neal Drive Peterborough, Ontario, K9J 7S4	20	High Alumina Ceramics Zirconia Ceramics
Industrial Ceramics Limited 473 Hensall Circle Cookesville, Ontario	10-15	Alumina and Circonium Silicate Ceramics
Polyceram Montreal, Quebec	N/A	Oxide Ceramics
Rolls-Royce Montreal, Quebec	N/A	Plasma Coatings
Pratt & Whitney	N/A	Plasma Coatings
George A Wright & Sons Ja-Division Kingston, Ontario	N/A	Plasma Coatings
Peacock Inc. 1180 Aerowood Drive Cookesville, Ontario	N/A	Plasma Coatings
Vacaro Montreal, Quebec	N/A	Plasma Coatings
Air Canada Montreal, Quebec	N/A	Plasma Coatings
CP Air Vancouver, BC	N/A	Plasma Coatings

7.3.5 Manufacturers of Cutting Tools

Companies manufacturing cutting tools are listed in Table 37. It is clear from the table that the majority of the companies are foreign subsidiaries. Nevertheless, there are a number of active Canadian companies who are potential candidates for developing advanced ceramic cutting tools in Canada.

F & S Tool Corporation, of Markham, Ontario, manufactures diamond and carbide cutting tools. It has about 50-75 people on staff.

Galtwood Tools, of Cambridge, Ontario, manufactures steel and carbide-tipped cutting tools, mainly for the woodworking industry. Staff strength is about 50. Over the years, the firm has developed a number of tools. The company is aware of advanced ceramic cutting tools and might be interested in developing them at a future date.

Graff Diamond Products Limited is located in Brampton, Ontario. It manufactures diamond-based cutting tools.

International Cutting Tools Limited, of Montreal, is a major Canadian cutting tool manufacturer. It has two plants in Quebec and a subsidiary in France (SENOCA). The total strength of the company is about 200. At present it manufactures only high-speed steel tools, mainly for the aerospace market. However, it is looking at other opportunities and may address advanced ceramic cutting tools in the future.

J.K.S. Boyles International Inc., of Toronto, is a wholly owned American subsidiary and manufactures diamond cutting tools. It employs about 50-75 people.

Lamage is a Division of J.K.S. Industries, which is linked to J.K.S. Boyle International. Lamage, located in North Bay, Ontario, manufactures diamond cutting tools used in the mining industry.

Kennametal Limited is the Canadian division of the American company of the same name. It has four operations in Canada. Kennametal Limited manufactures different types of cutting tools, carbide-based with CVD coatings. Kennrock Tools, located in Toronto, employs about 250 people and manufactures rock drilling and oil well drilling cutting tools, based on carbides and aluminum nitride. Kennametal in Victoria also manufactures carbide cutting tools. The Marco Division in Vancouver manufactures tungsten carbide powders which are used by other divisions in the manufacture of cutting tools. The R & D effort is small (about six people). Much of the R & D is conducted in the USA. Kennametal in the USA, has been manufacturing sialon cutting tools under licence from Lucas-Cookson. They are not yet made in Canada.

TABLE 37

Canadian Manufacturers of Cutting Tools

Company	Number of Employees	Products
F & S Tool Corp. Markham, Ontario	50-75	Carbide and Diamond Cutting Tools
Galtwood Tools Cambridge, Ontario	50	Carbide Tools
Graff Diamond Products Ltd. 35 Hale Street Brampton, Ontario		Diamond Cutting Tools
International Cutting Tools Montreal, Quebec	200	High Speed Steel Tools
*J.K.S. Boyles International Inc. 81 Tycos Drive Toronto, Ontario	50-75	Diamond Cutting Tools
*Lamage Division of J.K.S. Industries North Bay, Ontario	N/A	Diamond Cutting Tools
*Kennametal Limited 1425 The Queensway Toronto, Ontario	350	Tungsten Carbide Tools Alumina-Based Tools Sialon Tools
*Kenrock Tools Inc. 3370 Dundas Street West Toronto, Ontario	250	Tungsten Carbide Tools Alumina-Based Tools Sialon Tools
*Sandvik Canada Corp 6835 Century Drive Mississauga, Ontario	N/A	Carbide Cutting Tools
*Valenite Modco Limited Windsor, Ontario	200	Tungsten Carbide and Ceramic Cutting Tools

*Foreign owned companies

Sandvik Canada Corporation is a wholly owned division of Sandvik of Sweden. It has a manufacturing plant in Windsor to supply cutting tools to the automotive industry, and another in Montreal to supply the mining industry. Sandvik in Sweden has, under licence from Lucas-Cookson, the technology for manufacturing sialon cutting tools. Present plans do not call for bringing the sialon technology to Canada. However, the company may be interested in the future, particularly if incentives are made available.

Valenite Modco Limited, of Windsor, Ontario, is a subsidiary of the American company. It employs about 200 people, and manufactures carbide tools for the automotive industry.

7.4. Advanced Ceramics R & D in Federal Government Laboratories

Laboratories and organizations in the federal government that are conducting or supporting advanced ceramics related research and development programs are listed in Table 38.

Atomic Energy Research Establishment in Pinawa, Manitoba, has been involved for a number of years in the development of chemically resistant glasses for the safe disposal of nuclear wastes. Whereas the application is specific, the technology that is being developed is considered to have a much wider scope. It is expected to have significant impact in other applications.

Atomic Energy of Canada, Chalk River, Ontario, is working on ceramic processing technologies.

The Department of National Defence has been very active in support of advanced ceramics in some areas-both in-house and contracted out programs. Over the years, DREO (Shirley's Bay, Ottawa) has done a considerable amount of R & D - both in-house and contracted out programs - in a number of areas. Some of the programs are glass-ceramic-metal seals for battery and other applications and ceramics for diesel engines. The latter is a recently instituted program with sub-contract assistance from the Ontario Research Foundation.

DREP (Victoria, BC) has a number of programs on the development of advanced non-destructive techniques for use with advanced ceramics and composites. It has supported programs at ORF and McMaster University; the latter program is still in progress.

DREA, in Halifax, has established an interest in advanced ceramics for defense applications. Based on an in-depth study, DREA has instituted a number of programs: evaluation of the stability of advanced ceramics used in diesel engines; use of advanced ceramic technology for fire safety applications; and development of advanced piezoelectric materials for transducer applications. ORF is participating in the first two programs. The last one is being carried out by BM Hi-Tech Inc.

It is believed that the interest of the Department of National Defence in the development and use of advanced ceramics will increase, because of the tremendous advances being made in the USA and other NATO countries in this area; and the close inter-relationships in defence armament and systems between the countries.

The Department of Energy, Mines and Resources has been active in ceramic research for more than 50 years. The Ceramics Section of CANMET has been involved in the development of advanced functional ceramics for more than three decades. The pioneering work on barium

TABLE 38

Advanced Ceramics R & D Activities in Federal Government Laboratories

Organization	Activity
Atomic Energy Research Establishment Pinawa, Manitoba	Nuclear Waste
Atomic Energy of Canada Chalk River, Ontario	Ceramic Processing
DEPARTMENT OF DEFENCE	
Defence Research Establishment Shirley Bay, Ottawa, Ontario	Ceramics for Engines
Defence Research Establishment Atlantic, Halifax, Nova Scotia	Ceramics for Engines Ceramics for Fire Safety Piezoelectric Ceramics
Defense Research Establishment Pacific, Victoria, British Columbia	Non-Destructive Testing Ceramics for Transducers
DEPARTMENT OF ENERGY, MINES & RESOURCES	
Ceramics Section, CANMET	Dielectric Ceramics Ceramics for Energy Conversion Thermal Properties Ceramic Processing
NATIONAL RESEARCH COUNCIL	
Division of Chemistry, Ottawa Ottawa	Semiconductors Thin films
Division of Physics, Ottawa Ottawa	Optical Materials Optical Coatings
Division of Mechanical Engineering Ottawa, Vancouver	Tribology Ceramics for Engines
Division of Electrical Engineering Ottawa	Semiconductors Thin films
National Aeronautical Establishment Ottawa	Hot-Isostatic Pressing Non-Destructive Testing Composites
Industrial Materials Research Institute Boucherville, Quebec	Plasma Coatings Non-Destructive Testing Applications Technology Wear-resistance materials (WC) Semiconductor coatings PZT coatings and sensors

titanate piezoelectric materials, conducted in the 1950s, was the seed for two advanced ceramics companies in Canada - Almax and Lakeside Electronics. More recently, as part of the National Energy Program, important industrial work has been carried out in a number of areas: dielectric ceramics; ionic conductors (ZrO_2-oxygen sensors, ceramic electrolytes based on -alumina, NASICON, LISOCON, etc.), and hydrogen fuel cells. Important contributions have been made in the areas of material development, process development and property evaluation. The ceramic group of about 10 have extensive experience and expertise which should be used and for the benefit of the Canadian advanced ceramic industry.

The National Research Council (NRC) is also very active in some areas of advanced ceramics. A number of NRC divisions have undertaken related programs. The most focused work is conducted at the Industrial Materials Research Institute at Boucherville.

The NRC Chemistry Division in Ottawa has a very active group of about six people working on thin films and semiconductors, an area which is relevant to, and forms the basis for, an expansion of the advanced electronics industry base for applications such as communications, sensors, etc.

The Division of Energy supported a number of programs related to the development of advanced ceramics for energy-related applications. These programs included: development of advanced ceramic heat storage media (which formed the basis for an efficient heat storage system for off-peak power storage); advanced ceramic materials for solar collectors; advanced ceramic materials and technology for the development of "super-windows"; advanced glass-fibre technology for hydrogen storage; and advanced battery separators based on boron nitride. The latter has become the basis for new product lines being developed by the Electrofuel Manufacturing Company of Toronto.

The Division of Physics has been active for some time on optical materials, particularly coatings. In fact, the division has one of the best internationally recognized teams. Since sensors, opto-electronics and optical filters are expected to play a very important role in the future, this expertise should be very useful.

The Division of Mechanical Engineering has been very active in tribology (the science of wear and friction between materials). This is an important area because some of the important commercial applications for advanced ceramics are dependent upon their wear properties. More important, the division is responsible for engine research and has extensive facilities for testing and certifying engines. This division could, in the future, play an important role in introducing advanced ceramics for engine applications.

The Structures-Materials Section of the National Aeronautical Establishment, has a hot isostatic press (laboratory model) in use. In addition, the section has much expertise on the properties of materials (particularly composites). It is also very active in non-destructive testing. One of the keys for the rapid commercialization of advanced structural ceramics for engine applications is the development of non-destructive testing techniques. It appears that this group could contribute significantly in this area.

The Industrial Materials Research Institute is a special division of NRC, devoted to materials development and application. Its staff is 130, and the effort is divided as follows: plastics - 40 percent; metals and composites - 30 percent; coatings and ceramics - 10 percent; instrumentation and sensors - 17 percent; and administration - 3 percent. The institute is very active in a number of areas related to advanced ceramics: development of wear-resistant materials (WC-based); plasma coatings (based on TiB_2 for wear-resistant applications); semiconductor coatings for electrolyzers; thermal fatigue of refractories; PZT coatings using plasma techniques for sensors; and non-destructive testing, including opticalthermal inspection and acoustic microscope techniques. The institute is in a special position to expand its activities in advanced ceramics to meet national needs, for two reasons: first, it is already involved in a number of areas related to advanced ceramics which could easily be expanded; and second, it has the necessary capabilities, both in personnel and equipment, particularly in injection molding of plastics, to develop injection molding technology for advanced ceramics products. It also has a hot isostatic press capability.

In summary, the wealth of experience, expertise and knowledge in Canada in several federal government laboratories, could be harnessed to establish a national program on advanced ceramics, devoted to the development of generic R & D to support the needs of Canadian industry, particularly small business. In the United States, Japan, West Germany, United Kingdom and France, the facilities and capabilities of government laboratories are used to support national programs by assisting industry. These countries have been active in the development and commercialization of advanced ceramics for almost a decade, with thousands of research workers. The only way Canada could 'leap frog' to the latest technology and compete in world markets, is by harnessing the existing capabilities and facilities in government laboratories, together with other capabilities in universities, industry and provincial research organizations.

7.5 Advanced Ceramics R & D Activities in Canadian Universities

A list of Canadian universities where advanced ceramics related work is being carried out is given in Table 39. Only five universities, however, have significant groups in this area: University of British Columbia, McMaster University, University of Toronto, Queen's University and the Technical University of Nova Scotia.

The ceramics program at the University of British Columbia was initiated in the Department of Metallurgical Engineering, when, in 1959, Professor A.C.D. Chalklader joined the department. In the last 25 years, the department has contributed significantly, both in the training of ceramic engineers and in conducting R & D programs in a number of areas. Professor Chalklader is internationally known for his contributions to ceramics, particularly sintering, hot-pressing and mechanical properties. Professor J.S. Nadeau, head of the department, is also an internationally known scientist. His reputation is in fracture properties of ceramics. The department does not give degrees in ceramics. However, ceramics is an optional discipline taught to metallurgy students. At present the total strength of the group is about six.

McMaster University has been involved in the education of ceramic engineers for more than two decades. It initiated, in conjunction with the Canadian Ceramic Society, a course to teach ceramics in its extension division. A formal ceramics course was introduced in the Department of Metallurgy and Material Science in 1967, with the appointment of Professor P.S. Nicholson to the faculty. Over the years, Professor Nicholson and his students have contributed significantly to ceramic science and technology, specifically in sintering, mechanical and electrical properties. The group is also very active in assisting Canadian industry and government departments in development projects. Two areas where they have been active in recent years are in ionic conductors - particularly hydronium ionic conductors for hydrogen fuel cell development - and non-destructive testing of high-performance ceramics. Professor Nicholson is internationally known for his scientific contributions on high-temperature ceramic materials. The group has a staff of about 17. Recently, a new chair in Glass Science has been created, with the addition of Professor O. Johari. The university offers a formal degree in ceramics.

The University of Toronto had a formal ceramic degree course in the 1950s, but discontinued it because of lack of industry support for its students. However, the work was revived in the 1960s, although not on a formal degree basis. At present Professor B. Alcock, an internationally known specialist in high-temperature oxides, in addition to research activities in plasma technology, is teaching ceramics as part of the metallurgy and material science course. Professor D. Barham, in the Department of Chemical Engineering, has been active in ceramics research.

TABLE 39

Advanced Ceramics R & D Activities in Canadian Universities

University	Number of Investigators	Activity
McMaster University Hamilton, Ontario	17	Mechanical Properties Ceramic Processing Ionic Conductors, Bioglass
University of Toronto Toronto, Ontario	N/A	High Temp Oxide Chemistry Fibre Technology
Queen's University Kingston, Ontario	15-25	Ionic Conductors Piezoelectric Ceramics
University of Windsor Windsor, Ontario	2	Thin Films
Brock University St. Catharines, Ontario	2	Semiconducting Films
University of Western Ontario London, Ontario	3-4	Nuclear Ceramics
University of Waterloo Kitchener, Ontario	2-3	Mechanical Properties Solar Materials
University of British Columbia Vancouver, BC	N/A	Mechanical Properties Ceramic Processing
McGill University Montreal, Quebec	2-3	Development of Sialons Mechanical Properties Prosthetics
University of Montreal Montreal, Quebec	N/A	Oxide Ceramics Slip Casting
University of New Brunswick Frederickton, NB	2	Ionic Conductors
Technical University of Nova Scotia Halifax, Nova Scotia	4-6	Plasma Coatings Electrocatalysts
Laval University Quebec City, Quebec	2-3	Mechanical Properties

Queen's University in Kingston, Ontario, has a very active ceramics group led by Professor M. Sayer of the Department of Physics. Areas of activity include: piezoelectric materials (both monolithic and thin films); ionic conductors for battery and fuel cell applications; and transducer development. Professor R. Smith of the Department of Metallurgy, has initiated ceramic research, recognizing the importance of ceramics to industry, particularly in view of the international interest in this area. Queen's University has just announced the formation of an Advanced Materials Technology Unit, an interdepartmental-activity to promote advanced materials in general, and advanced ceramics in particular. The objectives of the unit are to bring together industrial companies, venture capital, government, and university facilities not only to promote research and development, but also to assist industry in product development. In the recent workshop organized by the Science Council of Canada, it was obvious that industry was not very happy with the assistance provided by universities in meeting their goals. The creation of the Advanced Materials Technology Unit at Queen's, is a very good first step in overcoming industry concerns, and should be commended and encouraged. It should be hoped that other universities will follow the lead of Queen's, and that industry and government will help create and support such groups. At present, the Queen's ceramic group has a staff between 13 and 25, including summer students.

The activities at the Technical University of Nova Scotia under the leadership of Professor H. King encompass a number of areas: electrocatalysts, conducting ceramics, plasma technology for erosion and corrosion-resistant ceramics and fire-resistant ceramics. It is a very active group, having contributed in the 1960s to the development of piezoelectric materials technology, the basis for two of the companies in advanced ceramics at present. This group could become an important part of a national activity on advanced ceramics.

Recently, research into advanced structural ceramics materials has been initiated at McGill University, under the leadership of Professor R. Drew.

In summary there are few Canadian universities active in ceramics, but those that are involved have an international reputation. They have a long, well-established history in research and development and are able to play an important role in enhancing Canadian activities in advanced ceramics, as well as assisting industry.

7.6 Advanced Ceramics R & D Activities in Provincial Research Organizations

Three of the provincial research organizations which have been active in ceramics R & D over the years are CRIQ, New Brunswick Productivity Council and the Ontario Research Foundation.

Over the years, CRIQ activity in ceramics has focused on assisting industry in the development of new products, new processes and improving productivity. To date, almost all of the activities have been in traditional ceramics. However, CRIQ is now addressing the opportunities in advanced ceramics and expects to increase its activities in the coming years. The present ceramic group has a staff of three. It is part of the Materials and Processing Division.

The New Brunswick Productivity Council does not have a formal ceramics group. However, a number of activities related to ceramics are in place. (see Table 40.)

The Ceramics Group at the Ontario Research Foundation is by far the largest and oldest group in Canada. It is internationally known for its contribution to ceramics science. More than 75 scientific and technical papers have been published by ORF staff.

Although assistance to industry has been provided by ORF since the 1930s, the Ceramics Group was formally created in 1959. Since then, the group has contributed significantly to the ceramic industry in Canada by providing R & D and testing services. Some of the important industrial clients have been: Corning Glass, Northern Pigment Co., Canadian Chromalox Co., Blue Mountain Pottery, BM Hi-Tech Inc., Almax Industries, Quality Hermetics, Holmes Insulation, Day Specialities Ltd., Design Precision Casting Co., Technifluids, and Neo Industries Ltd.

In addition to industry, ORF continues to provide R & D services to a number of federal government departments, particularly the Department of Energy, Mines and Resources, the National Research Council and the Department of National Defence. It has also participated in industrial projects supported by the Department of Industry, Trade and Commerce (now the Department of Reginal Industrial Expansion) through programs such as PAIT and EDP.

At present, the ORF Ceramics Group has a staff of about 25 scientific and technical personnel. It is the most well-established group and provides assistance to industry and government. It appears as though a new era in this activity is being opened, with part of the 'Centre for Materials' having opened at ORF, with assistance from the Province of Ontario. Some current activities are listed in Table 40.

TABLE 40

Advanced Ceramics R & D Activities in Provincial Research Organizations

Organization	Activity
CRIQ Quebec City, Quebec	Newly created advanced services group
New Brunswick Productivity Centre	Raw Material Processing Non-Destructive Testing Corrosion Battery Materials Development
Ontario Research Foundation Sheridan Park, Mississauga, Ontario	Sol-gel Technology - monolithic ceramics - flame-resisting applications - infra-red coatings
	Ceramics for Engines - ZrO_2 for diesel engines - erosion-corrosion properties - plasma coatings
	Non-Destructive Testing
	Ionic Conductors
	Piezoelectric Ceramics
	Advanced Ceramics
	- Boron Nitride
	- Glass Ceramics
	- Fibre Technologies

7.7 Threats and Opportunities for Canadian Industry

7.7.1 General

High technology has become not only the key to survival for many Canadian industries, but more important, will play a dominant role in creating new industries. In the past, Canada's growth has been generated primarily by exploiting natural resources. However, underlying economic pressures are forcing Canada to transform the impetus for economic growth from the mere exploitation of physical resources to the creation of high-tech industries which will help to transform the industrial infrastructure. The direction of the change will be toward higher value-added products, lower energy use, additional R & D - and more capital-intensive production. The fundamental economic challenge of the next decade is to shift the balance from dependency on natural resources to creation of wealth from high-technology products, and develop knowledge-intensive industries. That this trend is happening is clear from a comparison of the composition of Canadian exports from 1964 to 1984:

Product	% 1964	% 1984
Food	22.2	9.6
Crude Materials	19.4	15.6
Fabricated Materials	42.2	31.6
Vehicles & Parts	2.1	26.1
Machinery & Equipment	9.8	12.4
Consumer Goods	1.8	3.0
Other	2.5	1.6

That advanced ceramic materials play a pivotal role in the creation of high-tech products and industries, has been thoroughly demonstrated by Japan. During the 1970s, Japan developed sophisticated technology to exploit electronic ceramics, which paid off in two ways: first, by the creation of high-tech industries to manufacture electronic ceramic components, and second, by developing other high-tech industries, such as electronics, telecommunication, robotics and office automation. These in turn had a significant impact on the socio-economic well-being of Japan (in terms of jobs, export potential and improved productivity); and in general, through the creation of national wealth. Other industrialized countries such as the USA, West Germany, Sweden, the UK and France are following the lead of Japan. The unavoidable conclusion is that Canada has no option but to make a firm commitment to develop and sustain an advanced ceramics industry base to help create and support other high-tech industries.

In Japan and Canada, industry and society will be greatly affected as advanced ceramics come into wider use and the advanced ceramics industry develops. Their impact can be summed up in the following four points:

- As advanced ceramics technology develops and advances, various peripheral industries will come into existence, such as the compounding and design of materials to achieve the desired properties, and ceramic manufacturing equipment.
- The introduction and growth of an advanced ceramics industry will have a stimulating effect on local industry and regional economies.
- The entrance of enterprises into the field of manufacturing advanced ceramics will make it possible to vitalize the existing materials industry, strengthen international competitiveness and stimulate the growth of similar high-rated enterprises.
- The widespread use of advanced ceramics will have a beneficial effect on the national economy in energy savings, increased productivity and the creation of new jobs.

There seems to be a consensus that the engine of economic growth in Canada will not be 'resource development' as before. In fact, this sector has been slowing down, compared with other sectors, for several decades. As the above data show, export of food (mainly wheat) and crude and fabricated materials, accounted for 84 percent of Canada's export in 1964, but only 56 percent in 1984. This was not accidental. Canada's competitive advantage, at one time, was that resources existed here, that could be reliably developed and produced (with significant help from foreign investors). Now, other countries can attract that development activity more easily (particularly developing countries with a resource base that can be developed using low cost labour). Many Canadian resource companies, therefore, face exceptionally tough competition. In the global context, many existing Canadian production facilities look unprofitable. Advanced ceramics offer an alternative to these companies as a vehicle for diversification, to shift the focus of production into goods (and services) with a higher value-added end product where more technology, managerial and marketing skills are required.

Since the field of advanced ceramics is broad and the technology is still being developed, there is also plenty of room for smaller, high-rated companies to participate and grow. The strategies of these smaller, high-rated enterprises may be categorized, from the standpoint of manufacturing technology, into three main types:

- General manufacturing of advanced ceramics, both functional and structural;
- Orientation towards peripheral fields (i.e., manufacturing not advanced ceramics, but developing manufacturing equipment, tools, fixtures, etc., for the production of advanced ceramics);
- Specialization in each field in the manufacturing of functional parts and materials, such as sensors or optical ceramics.

The motives for enterprises to enter the advanced ceramics business can be grouped into three broad categories:

- Diversification by materials manufacturers to apply existing technology, achieve higher added-value and create more profitable products than ever before. In Japan, this is the motive for many companies in the textile, petrochemical and metal industries.
- Upgrading of existing technology, in which research and development of products a company has been producing (such as glass or refractories) makes it possible to give them new functions and properties, allowing them to change over into high added-value production.
- Participation by processing and assembling industries, in which the users of materials are led by necessity to develop new materials on their own. Typical examples of such industries are electrical and electronics, automotive, machinery, steel and heavy industry, and engineering.

Currently, the advanced ceramics business is like a marathon with a large number of entrants. The consensus is that the race is not yet half over, and all the runners are bunched together in a pack. **It is believed that in electronic ceramics (an especially high-skilled field) and in the development of sensors, small companies and venture businesses may emerge as strong runners. In the engineering ceramics, however, because of the nature of new ceramics businesses, large companies have the advantage.** Automakers who conduct joint studies with ceramics manufacturers have a big headstart in ceramic engines. There is consensus that auto manufacturers, that are putting a tremendous amount of effort into research and development, will probably keep the technology in-house, or at most, share it with a very few materials manufacturers. Some analysts believe, however, that materials manufacturers and other new entrants will take on the role of auto parts manufacturers either in business tie-ups or joint development projects with auto manufacturers.

To make up for lost time, latecomers to the advanced ceramics field (this applies to nations as well) will have to seek technology from business tie-ups with foreign manufacturers or more advanced domestic manufacturers. Talented people are what is needed to acquire and maintain technical prowess in advanced ceramics, but this does not mean that a company that is new to the field, or behind in technology, can take a sudden lead by simply scouting and acquiring talented people. Accumulation of technology and experience are the key issues.

7.7.2 Impact of International Development

As discussed earlier, there is intense international competition between the United States, Japan, West Germany and Sweden to develop and commercialize advanced ceramics because of the perceived large market potential in the coming decades, and the socio-economic benefits to be gained by capturing a significant market share. By default, Japan has to date taken the lead position. It has introduced commercially a number of ceramic components into diesel engines, is and planning others in the next few years. There is no certainty, however, that it can maintain this leadership position for long, let alone win the race. This uncertainty arises not because Japan is less committed to maintaining its present dominant share of the world market (estimated to be about 50 percent of all advanced ceramics); not because it is less willing to commit the huge resources required in terms of manpower and R & D funding; not because there is a change in its national strategy; but because the United States and West Germany have, albeit belatedly, recognized their vulnerable position and have implemented national strategies to gain momentum and to capture and maintain their market share. Furthermore, the United Kingdom, France and the European Economic Community, are taking positive steps to regain lost ground, vis-a-vis their market share and corresponding socio-economic benefits.

Canada is alone among the Western industrialized countries without a national position. In view of the present international activity, it is clear that Canada has to address the possible threats that might result to its socio-economic well-being by the developmental gains made to date elsewhere. on the positive side, it must take advantage of opportunities (i.e., Canada should enter the race not to win, but to gain a market foothold).

To identify threats and opportunities for Canadian industry, it is necessary to assess critically, and realistically, the present international position. Figure 28 schematically represents the forces that will have impact on Canada. Both West Germany and Sweden might directly affect Canada; West Germany, because Volkswagen is a participant in the autoparts activity in Canada, and Sweden, because it assembles Volvo cars in Canada.

Most of the impact, however, is expected to come from Japan and the United States: from Japan because of its technological lead; and the United States, because it is the biggest trading partner of Canada. It is important to consider the types of forces that exist in these two countries and address how they might affect Canada.

There is no doubt that Japan is the world leader in advanced electronic ceramics, as demonstrated by the fact that it holds the lion's share of the market (about 70 to 80 percent of world consumption). Three important reasons for this leadership are: recognition by the Japanese industry in the early 1970s of the importance of developing electronic ceramics to support electronics and other high-technology industries (e.g., communication, robotics, etc.); the availibility of scientific and technical knowledge in the literature generated mostly in the United States, UK and Europe which could be used to develop the products; and market development strategies, particularly the one of creating new markets, as opposed to fulfilling existing markets. The manufacturing technology know-how and expertise accumulated over a decade in commercializing electronic ceramics was very useful in addressing the technological developments related to advanced ceramics for engine and other applications. In fact, the present Japanese leadership in advanced ceramics, in general, is directly related to this advantage.

The technological barriers for commercializing advanced structural ceramics for engines are immense. Scientific and technical knowledge to solve some of these problems is still being developed. More important, after investing in R & D for almost eight years, there is immense pressure to justify investment of current sales rather than future market potential. Many companies are commercializing their existing technology, and the outcome of this is the development of industrial markets, such as pumps and wear parts, and consumer goods, such as knives and scissors. It appears as though big companies such

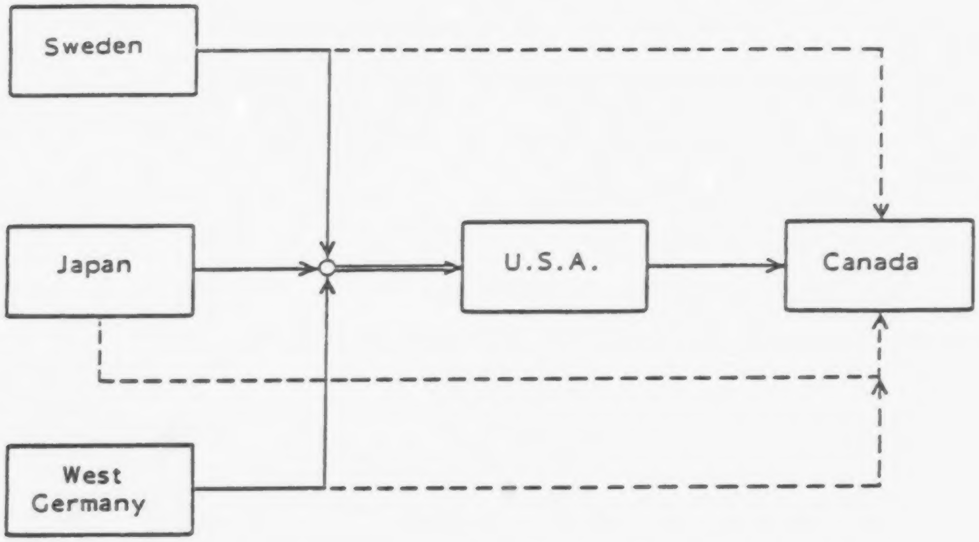

Sweden
Japan
West Germany
U.S.A.
Canada

FIGURE 28: International Pressure on Canada for World Market Share

as Toshiba, Sumitomo, Kyocera, NGK, are committed to the development of advanced structural ceramics for engines. Since these companies have immense resources and existing ceramic markets, they can justify the increased R & D effort devoted to the development of ceramics for engines, in view of the future market. Small companies do not have this option.

As for the future, there is no doubt that Japan will succeed in developing and commercializing advanced ceramics for engine parts. This will affect Canada in two ways: first, directly, because Japan's share of the Canadian auto market is about 23 percent and because Japanese companies may, in the future, participate in ceramic auto parts manufacturing in Canada; and second, since Japan has about a 24 percent share of the American domestic auto market, developments in Japan are expected to have impact on the American market which, indirectly, will affect Canada.

Because of the perceived threat from Japan, the United States has taken a number of steps to regain momentum in the development and commercialization of advanced structural ceramics. Both the federal government and American industry have taken positions: the former for increased funding for R & D both for demonstration projects and for pure research in universities and national laboratories, as well as private laboratories; the latter, for the development of advanced process and product technologies, particularly big companies. More than 1000 scientists and engineers are working in this area. The total estimated annual expenditure is about $100 million.

The US government initiatives are influenced by national security considerations as well as by socio-economic concerns. It is believed that the former will have a large impact on future plans and commitments. The advantages to be gained by incorporating advanced ceramics in engines in military vehicles (trucks, tanks, etc.) far outweigh cost considerations. It is likely, therefore that defense applications will lead the US market place. Besides, the material needs for the forthcoming 'strategic defence initiatives' are immense, and the ceramic development activities for defence applications are expected to accelerate at a fast rate.

Historically, the USA has always been the world leader in the development of science and technology. Since the solutions to some of the major barriers for the commercialization of advanced structural ceramics depend on breakthroughs in science and technology, the USA has an advantage, particularly since US industry is participating in the development of science and technology (e.g., at Rutgers, MIT, and Stanford).

The foregoing developments in the USA are expected to have a major impact on Canada for the following reasons:

- The USA is the biggest trading partner for Canada, accounting for more than 70 percent of exports.

- The North American Auto Pact offers opportunities for Canadian manufacturers (Canadian-owned as well as foreign subsidiaries) to participate in the expected business opportunities in advanced ceramics.

- The Canada-USA Defence Production Sharing Agreement provides additional opportunities for participation.

- Relatively cheap energy and abundant raw material resources in Canada (so close to the US border) and the big auto industry give Canada a particularly advantageous economic position.

- US industry and government are keenly aware of the Japanese achievements in advanced ceramics to date, and of the possibility of Japan obtaining a leading position in the anticipated large market. The USA is expected to react positively to keep its market share.

7.7.3 Opportunities in Advanced Functional Ceramics

The market for advanced functional ceramics is expected to grow rapidly to meet the requirements of other high-tech industries, both for domestic consumption and for export. At present, Canada has a relatively good industry base and infrastructure in electronics, communications, and computers. Others (such as robotics and biotechnology) are emerging, and are expected to grow substantially in this decade. All of these industries need advanced ceramics, and most of these needs are met by imports at the present time.

The results of this study indicate that a number of opportunities exist for the Canadian industry in this growing market - both for existing companies and for new companies yet to be formed. The opportunities are considered to be particularly attractive, from short-term and medium-term market needs. Furthermore, the opportunities are diverse enough to suit the needs of small, medium and large companies.

There is consensus in the technical community that the following areas in advanced functional ceramics will have significant impact in the market place in the short term to medium term (5 - 10 years).

- Fibre Optics
- Integrated Optics
- Multilayer Capacitators
- Semiconductors
- Piezoelectrics
- Pyroelectrics
- Ionic Conductors
- Sensors

The linkage between the technological areas and business areas is given in Table 41. With the exception of perhaps integrated optics, all other areas are under study or are manufactured in Canada. Market opportunities dictate that R & D efforts be expanded in areas which are already being investigated, and be initiated if no work is being done now. The last four categories of technologies are particularly suited to small- and medium-size companies, because they deal with speciality applications requiring strong technical background.

TABLE 41

Opportunities in Advanced Functional Ceramics for Canadian Industry

Technology Area	Business Area
Fibre Optics	Communication Information Systems
Integrated Optics	Communication Information Systems Optical Sensors Optical Signal Processing Optical Computing
Multilayer Capacitators	Electronics Computers
Semiconductors	Electronics Sensors Catalysts
Piezoelectrics	Transducers Sensors Electro-optic Displays
Pyroelectrics	Sensors Optical Devices
Ionic Conductors	Sensors Energy Storage (Battery) Fuel Cells Electrolysers Timers & Coulometers Heating Elements

Canada has a long history in research and development on electronic ceramics, going back to the 1950s. The pioneering work done by the Ceramics Section of the Department of Energy, Mines and Resources on piezeolectric ceramics, based on barium titanate, in the 1950s and 1960s gave Canada an international scientific stature, and formed the basis for the creation of the existing two manufacturing companies. More recently, this laboratory has been active in ceramics for energy-related applications, such as ionic conductors and fuel cells, an area which already has attracted industrial attention (e.g., Hamilton Porcelains Ltd.) in the development of electric vehicle batteries.

Northern Electric Co., in Ottawa, pioneered the development of magnetic ceramics in the 1950s and 1960s. However, its scope and activities have changed over the years to keep pace with developments in science and technology, as well as with demands and opportunities in the market place.

There seems to be no doubt that, from a short-term market point of view, the opportunities presented by advanced functional ceramics are immense. Since Canada has a very good industry base - small, medium and large companies - with a scientific and technical infrastructure in federal government laboratories, provincial research organizations, and universities, a coordinated effort should be made to harness these advantages.

7.7.4 Opportunities in Advanced Structural Ceramics

Opportunities for Canada in advanced structural ceramics can best be discussed in terms of three areas of activity:

- Ceramic Powders
- Non-Engine Applications
- Engine Applications

7.7.4.1 Ceramic Powders

Since a long-term market for advanced structural ceramics based on silicon carbide, silicon nitride and zirconia seems to be assured, the need for developing and commercializing suitable ceramic powders takes on a new dimension. International activity in this area is not as intense as in the development and commercialization of ceramic components, and there is room for scientific and technical innovation to develop new technologies. Furthermore, R & D is not considered as expensive as component development, testing and commercialization. Also, Canada has a number of large chemical companies that can undertake this activity supplementary to other maket opportunities.

Key requirements are low cost (about $5/kg), good quality and reliability of quality and supply.

Silicon Carbide (SiC) Powders

As mentioned earlier, a number of companies manufacture -silicon carbide in Canada because of a cheap and reliable electrical power supply. However, they are shipped to the US for processing. Opportunities for processing the powders should be explored. -silicon carbide is being developed especially for the manufacture of advanced ceramics. At present, this is not being manufactured in Canada and should be explored.

Silicon Nitride (Si_3N_4) Powders

Silicon nitride seems to be the preferred material. Demand for this powder is expected to increase as market penetration for these products increases. There are now a number of technologies for the manufacture of powder; however, there is also room for developing new processes. A number of manufacturers are commercially producing the powder in the USA, Japan and West Germany. Quality and cost are still problems. The former is being seriously addressed by the technical community and is expected to be resolved in the near future. Cost, however, will remain a problem until market penetration of the products increases and large-scale production reduces the manufacturing cost.

It is believed that opportunities exist for Canadian industry, (particularly existing ceramic powder manufacturers and chemical companies) to participate in this field. In a way the medium- to long-term nature of this market is an advantage because there is time for innovative approaches in developing new processes. The preferred route, however, will be technology transfer from existing foreign manufacturers. Alcan has already taken steps to address this opportunity.

Zirconia (ZrO_2) Powders

The market for zirconia-based advanced ceramics products is increasing. This appears, however, to be a very competitive market with Australia in the forefront. Canada has an advantage in that a good quality zirconia mineral source is available in northern Quebec. Exploitation of this mineral resource is a good opportunity for Canada, especially because this mineral is said to contain yttrium oxide, used not only in manufacturing toughened zirconia but also in the manufacture of silicon nitride ceramics.

7.7.4.2 Non-Engine Applications

Advanced structural ceramics have already penetrated the market in a number of non-engine areas, particularly industrial applications (chemical pumps, steel fabrication parts, heat-exchangers, welding nozzles, etc.), machinery parts and cutting tools, and consumer products. The properties for these products are not as severe as for engine applications. Moreover, technology already exists for the manufacture of these products.

It is believed that opportunities exist for Canadian companies to participate in this market. Technology transfer is the preferred method for getting into this market followed by new product development. Future success depends upon innovative approaches to create new markets by developing new applications.

The user industries in Canada for these materials are expected to be in the mining, steel, aluminum, and chemical process industries. One major mining company has indicated that wear-resistant material needs exceed $5 million per year. It is believed that the erosion/corrosion application market potential in Canada is more than $100 million per year.

Another growth market is in applications for leisure and consumer products.

7.7.4.3 Engine Applications

International competition in this area is severe, because of the perceived market potential which depends upon non-commercial considerations, such as national security, protection of domestic market, protection of market share in international potential, and other socio-economic issues. Countries such as the USA, Japan and West Germany (and to some extent Sweden) have invested huge sums of money over the last decade in developing and commercializing advanced ceramics for engine applications. Although the basic technology exists, there are a number of technological problems to be resolved: reproducibility in manufacture, reliability in service, and manufacturing cost. The USA, Japan, and West Germany are investing millions of dollars to resolve these problems. Japan appears to be in the lead, having already introduced a number of components and committing itself to an industrial strategy to increase market penetration.

The response of North American and European vehicle manufacturers for the introduction of ceramic components into engines is not as clear as that of the Japanese auto manufacturers. This is understandable because the priority at the present is to reduce cost to compete with Japanese imports. In any case, there appears to be consensus - even in Japan - that when the decision is made, they will either go into manufacture themselves or tie up with established ceramics manufacturers.

From the foregoing it is apparent that opportunities for Canadian industry are limited in the short term (0 to 5 years). In the medium term (5 to 10 years) and long-term (beyond 10 years), the opportunities appear to be satisfactory. If Canada wants to take advantage of future market opportunities, the time to make a commitment is now.

It is doubtful whether Canada can generate and invest the kind of resources that other countries have already committed (e.g., about 2000 scientists and 4000 technologists in Japan alone). In the investment decision, Canada has to take into consideration only the domestic market because it is likely that manufacturers in those countries that have committed huge sums of money already will try to protect their own markets. Besides, since Canada has to import the necessary technology from foreign companies, at least in the near future, there may not be many options.

In view of the North American auto agreement, Canada may be able to arrive at a beneficial arrangement with US companies. Similar arrangements could, perhaps, be made with Japanese and other foreign companies. In any case, technology transfer appears to be the preferred route from a commercial and business point of view.

Considering the huge future market potential and other socio-economic benefits than can be derived, Canada should consider the immediate mobilization of the infrastructure that already exists in federal government laboratories, provincial research organizations, universities and industry. Although small, the Canadian ceramic-related scientific community has an enviable record. (From 1953 to 1983 they contributed 326 scientific papers to the Journal of the American Ceramic Society, compared with 4440 from all US laboratories - a remarkable achievement.)

In all the countries that are active in the development of advanced ceramics, industry is the leading partner and governments are providing assistance. For future success, industrial participation is a prime requisite. As in the USA, in Japan and Europe, the Canadian government has to play a catalytic role in mobilizing industrial participation.

7.8 Opportunities, Barriers and Options

A critical assessment of world markets for advanced ceramics in terms of scope, timeframe and international competitive forces that exist to penetrate this market - particularly the significant lead already established by the USA, Japan, West Germany, and Sweden - indicate that Canadian industry can profit by taking advantage of the business and technical opportunities:

- Advanced Functional Ceramics, particularly electronic ceramics, integrated and fibre optics, sensors, and dental ceramics.
- Advanced Structural Ceramics for non-engine applications, particularly for industrial applications, cutting tools and consumer and leisure products.
- Advanced Structural Ceramics for engine and related applications.

Opportunities in advanced functional ceramics and advanced structural ceramics for non-engine applications are considered to be most appropriate for immediate consideration. In the former case, the market area is well established and the projected growth rate for the next two decades exceeds 15 percent. More important, there is already a considerable industry and R & D base, so that the future growth can be built on existing strength with minimal investment and time delay. Several large multinational companies are active in some of these areas and market forces are expected to accelerate their commitment for further expansion. This is an excellent growth area for existing small Canadian companies, as well as for the creation of new small enterprises.

The market for advanced structural ceramics in non-engine applications is more diverse, requiring innovative approaches for successful commercial penetration. It is expanding rapidly, however, because of materials substitution for existing applications to gain cost/performance advantages. Again, this is an area most suitable for small companies. However, large companies in the chemical, steel, aluminum, textile and other manufacturing industries may find it profitable to invest in this area to meet in-house requirements as well as to serve outside markets (including export). Cutting tools appear to be an exceptionally interesting market area, with good potential in the short term (0 to 5 years).

The technological and cost problems facing commercialization of advanced structural ceramics for engine applications are immense. Precisely for these reasons the North American auto manufacturers have not yet taken a definite position, although there is consensus that they will respond quickly if the Japanese are successful in their efforts. Market penetration and development, therefore, will take time. It is not expected to open up significantly for at least five years. Furthermore, competition from the companies who have invested in R & D in this area for almost a decade will be intense. Hence, opportunities for Canadian industry in this area are considered to be poor in the near term (0 to 5 years). In the medium term (5 to 10 years) and longer term (beyond 10 years), the market potential is expected to be substantial. In any case, this business area is suitable only for large companies, particularly those that already have a relationship with auto manufacturers. Only large companies can sustain the long-term investment commitment that is required. In a recent rationalization move to improve their competitive position vis-a-vis Japan, North American manufacturers not only reduced the number of parts suppliers, but also required them to do front-end R & D and adhere to just-on-time delivery.

Availability of abundant raw materials and relatively low-cost energy sources provide unique opportunities for existing ceramic powder manufacturers to expand their activities. As well, new companies can enter this field, particularly chemical companies. The future for Canadian success in this area is considered particularly bright. First, the need for low-cost reliable sources of ceramic powders is urgent to reduce the overall manufacturing costs of advanced ceramics. Second, Canada can 'leap-frog' in technological development through innovative R & D and technology transfer. Third, and most important, the number of committed powder suppliers is relatively small and there is room for Canadian suppliers to find a niche in the growing market.

A number of barriers have to be overcome to successfully take advantage of the identified opportunities. The most important barriers are:

- Availability of, or ability to develop, the required technology;
- Motivating multinational companies to expand or create new enterprises;
- Assistance to small companies, (existing as well as new) particularly for market development.
- Availability of the required technical personnel.

Availability of technology is perhaps the biggest barrier. Almost all the technology developed elsewhere to date is protected by patents. Hence, as a first step, technology transfer by licencing agreements is the best route to follow. With limited resources, financial as well as personnel, Canada cannot afford to embark on a basic R & D program. Rather, specific business opportunities should be identified and developed.

Although Canada has a relatively good R & D base in universities, provincial research organizations, and federal government laboratories, these capabilities are not harnessed effectively by establishing long-term objectives of national interest, nor are they supported by good planning, coordination and the required funds. This does not greatly affect multinational companies and larger Canadian companies because these companies have access to technology from the parent company or through licensing agreements. However, smaller companies (existing as well as new), that have generally limited capability or access to technology - and who could benefit considerably - are adversely affected.

The small size of the Canadian domestic market for advanced ceramics, compared with that of the USA and Japan, may discourage multinationals from investing in Canada. However, the North American Auto Pact, the Defence Procurement agreement with the USA, relatively low labour costs and availability of abundant energy (at low costs) may have significant influence on these companies investing in Canada.

Almost all the small companies consulted as part of this study indicated that identification of markets is relatively easy, but that developing the market opportunities is expensive. Financial assistance programs to develop and penetrate the markets are required.

Availability of technical personnel is another serious barrier. At present there is only one university - McMaster - that is graduating ceramic engineers. Methods of increasing the supply of qualified technical people to support industry as well as R & D organizations have to be addressed. Queen's University has just started an Advanced Materials Technology Centre as a cooperative effort between industry, university, government and venture capital to promote industrial R & D. This and other similar 'group' activities should be promoted.

The Government of Ontario has announced, within the framework of the Enterprise Ontario Program, the creation of a Centre for the Commercialization of Advanced Industrial Materials (including advanced ceramics) at the Ontario Research Foundation at a cost of $10 million over three years. This undoubtedly, is welcome news for the industries of Ontario.

From a national point of view, Canada has three broad options to promote and strengthen advanced ceramics activities in Canada, both in the manufacturing sectors and in research and development organizations, private as well as public:

- It can seek to accommodate the special needs of the advanced ceramics sector within the existing framework of assistance programs.
- It can move deliberately towards expanding the existing framework by adding special provisions.
- It can, as in the USA, Japan, West Germany, Sweden, and the United Kingdom, recognize the importance of advanced ceramics for the socio-economic well-being of Canada, and adopt similar programs.

The third option is the preferred option. The basic aim of this option would be, over time, to lessen the vulnerability of the Canadian economy to developments in the USA and Japan, the leaders in advanced ceramics that can have an impact on Canada. On the positive side, Canada can take advantage of opportunities to assist industry, particularly small business enterprises (existing as well as new). The policies and programs adopted by MITI in Japan - particularly the 'catalytic' role to promote industrial commitment - are acclaimed as the best in the world. Therefore, they could be used as models in identifying and implementing policies and programs most suitable and appropriate to meet Canadian needs. Typically, the Government of Canada could adopt a national leadership and coordination role to:

(a) Identify and establish a national program with specific technical objectives to meet industry and business needs;

(b) Support and coordinate the activities of the federal government laboratories in carrying out the national specific programs;

(c) Use universities and provincial research organizations to support national objectives to assist industry.

Finally, it is suggested that a joint council between industry, government and universities be set up as an advisory body to identify and recommend the goals and objectives of the national program.

BIBLIOGRAPHY

1. W.D. Kingery, H.K. Bowen
Introduction to Ceramics
2nd Edition, John Wiley & Sons (1976)

2. John J. Burke, Alvin E. Gorman and R. Nathan Katz (Editors)
Ceramics for High Performance Applications

3. Edward M. Leone, R. Nathan Katz, and John J. Burke (Editors)
Ceramics for High Performance Applications III, Reliability
Plenum Press. (1983)

4. F.L. Riley (Editor)
Progress in Nitrogen Ceramics
NATO ASI Series
Martinus Nijhoff Publishers (1983)

5. George B. Kenny and H. Kent Bowen
High-Tech Ceramics in Japan: Current and Future Markets
Bul. Am. Ceram Soc. 62 (5) pp 590 - 596 (1983)

6. James I. Mueller
US Needs Ceramic Program for Heat Engines
Ceramic Industry, May 1984, pp 22-25

7. John Bell
The New Ceramics Age Dawns
New Scientist 26 January 1984, pp 10-22

8. Howard J. Sanders
High-Tech Ceramics
Chemical & Engineering News, July 1984 pp 26 - 40

9. Robert A. Harmon and Charles W. Beardsley
Ceramics Heat Up
Mechanical Engineering, May 1984 pp. 22 - 43

10. Arthur F. McLean
Ceramic Technology for Automotive Turbines
Bul. Am. Ceram. Soc. 61 (8) 861-871 (1982)

11. Toshio Shishido
Japanese Industrial Development and Policies for Science and Technology
Science Vol. 219, pp 259-264 (1983)

12. R. Naito
Aspects of Japanese Ceramic Industry
J. British Ceram Soc. 6 (1) 1969

13. Shinroku Saito
The Current Outlook for Japanese Ceramics.
Bul. Am. Ceram. Soc.

14. Seiji Iwata	R & D on High Technology Ceramics in Japanese Industries Bul. Am. Ceram. Soc., 61 (9), pp 926-928 (1982)
15. Hiroaki Yanagida and Mitsue Koizumi	Major Ceramic Research Programs Sponsored by the Japanese Government Bul. Am. Ceram. Soc., 61 (9) pp 929-939 (1982)
16. Osamu Fukunga and Yusuke Morisyoshi	Research at Japanese National Laboratories Bul. Am. Ceram. Soc. 61 (9) pp 923-925 (1982)
17. H. Kent Bowen and Joseph A. Pask	Learning from Japan's Developments High Technology Ceramics Bul. Am. Ceram. Soc. 61 (9) pp 916-918 (1982)
18. S.R. Skaggs	Report on Trip to Japan Los Alamos National Laboratory May 1982
19. L.R. Johnson, A.P.S. Teotia	A Structural Ceramic Research Program: A Preliminary Economic Analysis Report No. ANL/CNSV-38, March 1983 Argonne National Laboratory (Sponsored by Dept. of Energy)
20. US Commerce Department	A Competitive Assessment of the US Advanced Ceramics Industry. Published by US Commerce Dept. PB84-162288, March 1984
21. Oak Ridge National	Ceramic Technology for Advanced Heat Engines: Program Plan ORNL/TM-8896, June 1984
22 Charles River Associates	Technical and Economic Assessment of Advanced Ceramic Materials 1984: Vol. 1: Summary and Conclusions Vol. 2: A Case Study of Ceramics in Heat Engine Applications Vol. 3: A Case Study of Ceramic Capacitors Vol. 4: A Case Study of Integrated Optic Devices Vol. 5: A Case Study of Ceramic Toxic and Combustible Gas Sensors Vol. 6: A Case Study of Ceramic Cutting Tools

23. A.G. Evans	Technical and Scientific Assessment of the Reliability of Advanced Ceramics, July 1982 Report prepared for National Bureau of Standards
24. National Academy of Sciences National Research Council Washington, D.C.	High-Technology Ceramics in Japan 1984
25. The Long-Term Credit Bank of Japan, Ltd.	Japan's High Technology Industries (2) February 1984
26. The Ministry of International Trade and Industry	Report of the Working Group on Fine Ceramics and Fundamental Issues, May 1984
27. Yano Research Institute Ltd.	New Ceramics Market in Japan, August 1982
28. Department of Energy, Mines and Resources, Ottawa	Ceramic Plants in Canada Operators List 6, 1975
29. Hatch Associates Ltd. Toronto	Assessment of the Needs and Opportunities in Advanced Materials Technologies, April 1984
30. C.M. Chirin	Advanced Industrial Materials in Japan, August 1983

APPENDIX A

Government Agencies, Laboratories, Industrial Companies and Universities Visited in Europe, Japan and the United States

No.	Institution	Name and Position
1	Imperial College of Science and Technology London, England	Dr. P.S. Rogers Assistant Director Dept. of Metallurgy
2	Morgan-Matroc Ltd. Stourport-on-Severn, England	Dr. B.G. Newland Technical Director
3	British Ceramic Research Association Penkhull, Stoke-on-Trent, England	Mr. David Loyd Head, Advanced Ceramics
4	University of Newcastle Newcastle-upon-Tyne, England	Professor K.H. Jack Dept. of Metallurgy
5	University of Leeds Leeds, England	Professor R.J. Brook Head, Ceramics Dept.
6	UK Atomic Energy Research Establishment Harwell, England	Dr. D.T. Livey Head, Materials Division Dr. Davidge Head, Ceramics Section
7	Desmarquest Laboratoire de Recherches Trappes, France	Dr. Jean-Paul Torre Chef du Laboratorie
8	Universite Paris Sud-Orsay, Paris, France	Dr. Jean Phillibert C.N.R.S.
9	Ecole Nationale Supérieure de Ceramique Industrielle Limoges, France	Professor Philippe Boch Directeur
10	ASEA Cerma Robertsfors, Sweden	Dr. Hans Larker Managing Director
11	Sandvik Hard Materials Stockholm, Sweden	Mr. Ernst Ake Nylander Director of Research
12	Svensk Silikatforskningsinstitutet Gothberg, Sweden	Dr. Roger Carlsson Manager
13	Bundesministerium Fur Forschung und Technologie Bonn, West Germany	Dr. Daniel Widdershoven Regierungsdirector
14	Deutsche Forschungs - und Versuchanstalt fur Luft - und Raumfahrt e. V. Koln West Germany	Dr. Ing. G. Ziegler Abteilungsleiter Dr. Wolfgang Braue

No.	Institution	Name and Position
15	Electroschmelzwerk Kempten GMBH Munchen, West Germany	Dr. Alfred Lipp Prokurist und Leiter der Erntwicklung
		Mr. George Rabini General Sales Manager
16	SIGRI Elektrographit GMBH Meitingen, West Germany	Mr. Hugo Eicher General Manager
		Dr. Werner Klose Technical Manager
17	Daimler Benz A.G. Stutgart, West Germany	Dr. Klaus Morgenthaler Head, Ceramics Group
18	Max Planck Institut fur Metallforschung Institut fur Werkstoffwissenschaften Stuttgart, West Germany	Dr. P. Greil Dr. N. Clausen
19	Volkswagenwerk Wolfsburg, West Germany	Mr. Langer Senior Engineer
20	H. C. Starck Co. Goslar, West Germany	Dr. G. Schwier Technical Director
21	Toshiba Ceramics Co. Ltd. Tokyo, Japan	Dr. Hideo Nagashima Managing Director
		Dr. K. Ban Manager, Technical Admin.
22	Toshiba Corporation Toyko, Japan	Dr. Ken-Ichiro Ando Senior Managing Director
		Dr. Katsutoshi Komeya Senior Scientist
23	Showa Denko, K.K. Toyko, Japan	Dr. Junichi Sato Deputy Chief Manager
		Dr. Yoshitaka Technical, Manager
24	NGK Insulators Ltd. Nagoya, Japan	Dr. Iwao Kikoto Managing Director
		Mr. M. Okuba Manager, Planning

No.	Institution	Name and Position
		Mr. Tsuneji Izumi Manager, Product Engineering
25	NGK Spark Plug Co. Ltd. Nagoya, Japan	Mr. Isamu Fukura Managing Director
		Mr. Takehiko Kato Assistant, Manager, Research
26	Kobe Steel Ltd. Kobe, Japan	Mr. Nobuyasu Kawai Manager, New Materials
		Mr. Hiroshi Takigawa Senior Metallurgist
		Mr. K. Homma Ceramic Engineer
27	Murata Manufacturing Co. Ltd. Kyoto, Japan	Dr. Kikuo Wakino Senior Executive Director
28	Ube Industries Ube, Japan	Mr. Tadashi Iwai Manager, Ceramic REsearch
		Mr. Hiroyuki Asade Associate Manager
29	Osaka University Osaka, Japan	Dr. Mitsue Koizumi Professor of Mineral Science
		Dr. Yosinari Miyamoto Associate Professor
30	Ministry of International Trade and Industry (MITI) Tokyo, Japan	Dr. Yoshihiro Adachi Director, Fine Ceramics Office
		Dr. Shina Aoki Senior Officer, Basic Technology
31	Japan Industrial Technology Association, (JITA), Tokyo Tokyo, Japan	Dr. M. Suzuki Senior Executive Director

No.	Institution	Name and Position
32	Engineering Research Association for High Performance Ceramics Tokyo, Japan	Dr. Kiyoshi Nakamura Senior Managing Director
		Dr. Akio Nagahiro Managing Director
33	Science and Technology Agency (STA) Tokyo, Japan	Dr. Yukio Sato Director, Office of Materials, Science and Technology
34	National Institute for Research in Inorganic Materials (NIRIM) Sakura-Mura, Niihari-Gun, Ibaraki, Japan	Dr. Masaru Goto Director General
		Dr. Yoshiro Inomata Supervisor, SiC Group
35	Government Industrial Research Institute (GIRI) Nagoya, Japan	Dr. Shunji Nagase Director
		Dr. Eiichi Nagase Director, Ceramic Engineering
36	Ford Motor Company Scientific Laboratory Dearborn, Michigan, USA	Dr. Thomas J. Whalen Principal Research Scientist
		Mr. John A. Mangels Ceramic Engineer
		Dr. Morton E. Milburg Senior Scientist
37	The Center for Ceramics Research The State University of New Jersey Piscataway, NJ, USA	Dr. J.B. Wachtman Director
		Dr. Lisa C. Klein Associate Professor
38	National Bureau of Standards Gaithersberg, Md., USA	Dr. Samuel J. Schneider Deputy Chief Inorganic Materials Division
		Dr. Sheldon M. Widerhorn Senior Research Scientist

No.	Institution	Name and Position
39	National Academy of Sciences National Research Council Washington, DC, USA	Dr. Richard M. Spriggs Senior Staff Scientist
40	SRI International Menlo Park, Calif., USA	Dr. Gerald Shroff Director Materials and Metalworking

APPENDIX B

List of Persons in Canada Who Participated in Discussions

No.	Organization	Name and Position
1	McMaster University Hamilton, Ontario, Canada	Dr. P.S. Nicholson Professor, Dept. Metallurgy and Materials Science
2	Queen's University Kingston, Ontario Canada	Dr. R.W. Smith Professor and Head, Dept. Metallurgical Engineering
		Dr. M. Sayer Professor Department of Physics
3	University of British Columbia Vancouver, BC Canada	Dr. A.C.D. Chalklader Professor, Dept. of Metallurgy and Material Science
4	University of Toronto Toronto, Ontario Canada	Dr. D. Barham Professor Dept. of Chemical Engineering
5	B.M. Hitech Inc. Collingwood, Ontario Canada	Dr. E. Prasad General Manager
6	Electrofuel Manufacturing Co. Toronto, Ontario Canada	Dr. Shankar Das Gupta President
7	Hamilton Porcelains Ltd. Brantford, Ontario Canada	Mr. A. Mason President
8	EYC Technical Ceramics Inc. Espanola, Ontario Canada	Mr. Robert G. McEwen Project Manager
9	Alcan International Ltd. Kingston, Ontario Canada	Dr. Raman R. Sood Director of Research
10	Ontario Research Foundation Sheridan park, Ontario Canada	Mr. J. Johnston Vice President Business Development

No.	Organization	Name and Position
11	Sandvik Canada Corp. Mississauga, Ontario Canada	Mr. E.A. Thompson Manager
12	Iron Ore Co. of Canada Sept-Iles, PQ Canada	Dr. Bis Chanda Supt. Special Projects
13	Ontario Centre for Automotive Parts Technology St. Catharines, Ontario Canada	Mr. George A. Lacy President
14	Litton Systems Canada Toronto, Ontario Canada	Dr. A. Baryani
15	National Research Council Ottawa, Ontario Canada	Dr. W. Wallace Head, Structures and Materials
16	Department of Energy, Mines and Resources Ottawa, Ontario	Mr. K.E. Bell Head, Ceramics Section
		Dr. T.A. Wheat Research Scientist
17	Bell Northern Research Ottawa, Ontario Canada	Dr. W. Westwood
18	Metco Canada Division Perkin-Elmer (Canada) Limited Rexdale, Ontario Canada	Mr. B. Royea Sales Manager
19	International Cutting Tools Inc. Montreal, PQ Canada	Mr. A. Minicozzi
20	Canadian Corporate Management Ltd. Toronto, Ontario Canada	Mr. W. Irwin Technical Director
21	Kenrock Tools Inc. Toronto, Ontario Canada	Mr. Justin Chan

No.	Organization	Name and Position
22	Lamage, Division of J.K.S. Industries North Bay, Ontario Canada	Mr. John Nicols
23	Valenite Madco Inc. Windsor, Ontario Canada	Mr. B.N. Slugs
24	J.K.S. Boyles International Inc. Toronto, Ontario Canada	Mr. John McGibbon
25	Home Technics Ltd.	Mr. Karl A. Kappes
26	CRIQ	Dr. F. Dugal Director Materials and Process Division
27	IBM	Mr. R. Champagne
28	Epitek Electronics	Mr. S. Tasker
29	Almax Industries (1980) Ltd.	Mr. Kamal El Assal
30	Technical University of Nova Scotia	Dr. H. King
31	Pyrotanax	Dr. T. Tymowski
32	Galtwood Tools	Mr. A. Milton Sales Manager